Livestock futures in a changing world: Modelling interactions between animal agriculture and the environment

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Chapter I: Introduction

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1. Background

1.1. Livestock in the Anthropocene

Since the onset of the Industrial Revolution, human activities have become a driver of environmental change to an extent that sets them amongst the great forces of nature (Rockström et al., 2009; Steffen et al., 2007). To denote the role of humanity in shaping Earth system processes, a new term was suggested for the current geological epoch: the Anthropocene (Crutzen, 2002). The rise of this new epoch saw not only human population growing to orders of magnitude above the pre-industrial level, but also the number of domestic animals skyrocketing in an unprecedented way. At present, livestock biomass is more than twice the weight of humans and wild megafauna taken together (Barnosky, 2008).

Current levels of human appropriation of biomass are estimated to account for 16% of global terrestrial NPP (Krausmann et al., 2008). Only 12% of the economically used plant biomass is directly used as food (Krausmann et al., 2008), while the lion's part (~ 60%) enters the livestock sector as feed. Around two thirds of the Earth's surface is to varying degrees directly affected by the process of biomass production to provide food, feed and raw materials (Erb et al., 2007), while only about one fifth of the terrestrial surface may still be classified as "wilderness" (Sanderson et al., 2002). No ecosystem on Earth can be regarded as completely untouched by human interference anymore (Vitousek et al., 1997).

Because of the strong interconnectedness of land with vital aspects of the Earth system and the extend of past and ongoing land transformation, land use and land cover changes have been a key driver of human alteration of terrestrial ecosystems during the last 50 years, interacting with most other aspects of global environmental change and affecting biogeochemical cycles (Lambin et al., 2001; Vitousek et al., 1997). Livestock is at the epicentre of land related human interference with Earth system processes. Grazing land for ruminants alone accounts for 26 percent of the terrestrial surface of the planet (Steinfeld et al., 2006). Including land requirements of feed cultivated on cropland, overall land use associated with livestock production accounts for 80% of agricultural land (Steinfeld et al., 2006).

Livestock, land and the environment are closely interconnected in a manifold of processes. Feed production fuels the competition for land, driving deforestation and carbon emissions, entails water withdrawals for irrigation and substantially adds to the agricultural nitrogen cycle, with nitrogen returning to the environment in the form of manure. The interplay between the different aspects of the livestock-environment nexus is imbedded in the context of a rapidly changing world. Population growth, increasing incomes and urbanization notably in developing countries will intensify the pressures on agricultural systems and ecosystems around the world. Climate change is expected to put further strain on food production.

The rising demand for food will be accompanied by a diet shift towards livestock products. The combined effects of population growth and a transformation of dietary patterns implicate a huge transformation of agriculture, a continuation of the "Livestock Revolution" (Delgado et al., 1999). The upsurge of livestock farming in the Anthropocene has not yet reached its limits. This thesis explores how future livestock production will shape the environmental footprint of agriculture, where special attention is given to land, nitrogen, water and carbon.

1.2. The hoofprint of livestock production

Over the course of recent years, an increasing body of scientific literature has revealed the considerable extent to which livestock production contributes to major environmental problems, arising across scales, regions and production systems. One of the milestones was the publication of the report "Livestock's Long Shadow" (Steinfeld et al., 2006) by the Food and Agriculture Organization (FAO). Amongst the key messages was the emergence of the livestock sector as one of the top two or three causes of the most severe environmental problems. In order to find solutions for the pressing symptoms of global change, such as climate change and air pollution, water shortage and water pollution, land degradation and loss of biodiversity, there is no way around the growing livestock sector. Between the poles of livestock's large environmental footprint and the magnitude of past and expected growth of the livestock sector, a fruitful scientific debate evolved since then, exploring possible ways out of this dilemma without further compromising ecosystem functioning and advances in improving food security in developing regions (Herrero et al., 2015).

The following subsections intend to give an overview on key interactions of animal agriculture with the environment.

1.2.1. Land

There is a strong connection between livestock and land that translates into many other livestock-environment interactions, since e.g. biodiversity and the terrestrial carbon balance are subject to the extent of land under management and changes in land use (Lambin et al., 2001). As the largest human land use activity, livestock farming is shaping whole landscapes and its hunger for land, either pasture for grazing or cropland for cultivation of feed crops, entails further alteration and fragmentation of natural habitats and encroachment into the remnants of undisturbed ecosystems (Herrero et al., 2009; Steinfeld et al., 2006). Land is constitutional for human societies not only by delivering the core products like food, fibre, wood and other raw materials for which its management is designated in the first place, but also by providing essential intermediate services like water and nutrient cycling, soil formation, equitable climate and biological diversity (Dunlap and Catton, 2002; Smith et al., 2013; UK National Ecosystem Assessment, 2011).

Deforestation is the most critical aspect of global land use change, with livestock playing a pivotal role. The scientific debate on livestock and deforestation is centred around two main forms of appearance, the clearance of forests to establish pastures for extensive cattle enterprises and conversion of forests into cropland for producing crops like soybeans mainly for export and to feed typically animals in industrialized production systems (Herrero et al., 2009; Nepstad et al., 2006). The contribution of forest-to-pasture conversion alone is estimated to be around 65-80% of the total deforestation of the Amazon (Herrero et al., 2009; Wassenaar et al., 2007). While cattle ranging is the major direct driver of forest conversion, there are indirect mechanisms through which soybean production is triggering deforestation, like driving up land prices and establishing infrastructure (Barona et al., 2010; Fearnside, 2001, 2005; Nepstad et al., 2009). Expected growth in trade of feed and livestock products is likely to drive expansion of the area used for soybean cultivation (Naylor et al., 2005).

The multitude of severe regional and global impacts attributable to the expansion of agricultural land into native forests include deterioration of water quality and alteration of hydrological cycles, involving changes in precipitation patterns, run-off and evapotranspiration (Costa et al., 2003; McAlpine et al., 2009; Rost et al., 2008). Moreover, loss of the environmentally sensitive rainforests implies a severe decline of biodiversity, both through reduction of total area and fragmentation of remaining natural vegetation (Laurance et al., 2002; MEA, 2005). Considered together, deforestation caused by extensive cattle production and feed cultivation are responsible for around 2.4 billion tons of CO_2 emissions worldwide (Steinfeld et al., 2006). Accordingly, restraining land requirements related to livestock production is increasingly regarded key to alleviate detrimental impact of livestock on the environment (Herrero et al., 2013; Smith et al., 2013; Steinfeld and Gerber, 2010; Wirsenius et al., 2010).

1.2.2. Biomass

The type and amount of biomass flows entering the livestock sector as feed establish the link between livestock and land (Herrero et al., 2013). Thus, studies that quantify the environmental footprint and resource efficiency of livestock production evolve around estimates of the feed base, i.e. feed efficiencies, feed basket composition and total feed use, as centrepiece of the analysis (Bouwman et al., 2005, 2013; Herrero et al., 2013; Wirsenius, 2000; Wirsenius et al., 2010). Globally, grazed biomass represents the most important feed resource (Herrero et al., 2013), supplemented by forage crops currently covering 34% of cropland (Steinfeld et al., 2006), food crops, various food crop residues, food industry byproducts from food processing and occasional feed like food waste and roadside grazing. Livestock farming and plant production are intertwined along the agricultural and food supply chain. While animal feeding is an important driver of agricultural biomass production competing with other potential usages of biomass, various residues and by-products generated in the food system can be recycled and utilised as feed. Feed can be sourced from inedible biomass and land with no or little alternative value for food production, thus representing a net contribution to food supply. However, due to large-scale deployment of food crops, livestock feed is in direct competition with human food.

As a consequence, how much and what kind of biomass is used to feed animals entails implications for the complex relationship between livestock and food security (Erb et al., 2012). Due to the considerable range of possible feed sources including biomass which cannot be directly metabolized by humans, feed demand of the global animal population also contends with other destinies of biomass, like manufacturing, industrial processing within a transformation towards the bioeconomy, and increasingly with biomass utilization in the energy sector, especially in the context of second generation biofuels which are very flexible in respect to the required feedstock. Since plantations delivering feedstock for second generation biofuels can be established on marginal land (Tilman et al., 2006; Zomer et al., 2008) and even cellulosic and heterogeneous biomass, crop residues, conversion by-products and waste can be used for the generation of energy (Cantrell et al., 2008), there could emerge another hotspot of future trade-offs with regard to livestock production.

1.2.3. Water

Around the world, more than half of fresh and accessible runoff water is used by human enterprises, with agriculture contributing the largest share to anthropogenic water use (Postel et al., 1996). Water is essential to all life on Earth. Neither for natural ecosystems nor for most human uses, water is substitutable and depletion or pollution of this valuable natural resource implies disastrous consequences for both nature and human societies, affecting health, fueling possibly violent resource conflicts and restraining agricultural as well as industrial production (Postel et al., 1996; Vitousek et al., 1997). Agricultural water use either stems from green water resources (naturally infiltrated rainwater in the soil) or from blue water resources (irrigation water withdrawn from rivers, lakes and aquifers) (Hoekstra and Chapagain, 2007).

Depending on the climatic conditions and production methods, 1 to 5 m^3 of water are needed to produce 1 kg of grain, while 5 to 20 times more water is required to produce 1 kg of livestock commodity (Chapagain and Hoekstra, 2003). Livestock related water use largely depends on the amount and type of biomass entering the livestock sector as feed and is estimated to account for roughly one third of agricultural water use (de Fraiture et al., 2007; Herrero et al., 2009). This estimate includes water transpired from grassland systems, for which the literature offers a large range of diverging assessments. Estimates of water use involved in livestock farming are subject to large uncertainty and knowledge about the current and possible future contribution of livestock to water depletion is still incomplete. Several authors note that the livestock-water nexus has widely been disregarded by both water and livestock research communities (Bossio, 2009; Cook et al., 2009; Herrero et al., 2009; Peden et al., 2007; Thornton and Herrero, 2010). Yet, understanding the impacts of livestock on water resources is essential to address the water challenge of feeding a growing population with changing dietary preferences towards animal-based products (Rosegrant et al., 2009; Valin et al., 2014a).

Compared to water use for feed cultivation, water requirements for drinking and servicing are very small, representing only 0.6 of global freshwater use (Steinfeld et al., 2006). However, a considerable proportion of drinking and service water re-enters the environment as manure and wastewater. Depending amongst other factors on the intensification level, animal waste management and environmental regulations, these water backflows contain numerous pollutants like drug residues, heavy metals and pathogens and a substantial amount of nutrients (nitrogen, phosphorous and potassium) (Steinfeld et al., 2006). The fraction of nutrients in manure in relation to total soil nutrient inputs are estimated to reside at 14% for nitrogen, 25% for phosphorous and 48% for potassium (Herrero et al., 2009; Sheldrick et al., 2003). Especially surpluses of nitrogen represent a major threat to water quality and aquatic ecosystems leading to eutrophication with severe impacts on the mix of aquatic plants, habitat characteristics as well as aquaculture and fisheries (Grizzetti et al., 2011; Steinfeld et al., 2006).

1.2.4. Nitrogen

Although nitrogen exists in plethora in the atmosphere in its stable form (N_2), its availability as reactive nitrogen (N_r), which is fixed and accessible for most organisms, was for a long time limited and a restraining factor for agricultural activities (Bouwman et al., 2013; Smil, 2002). Productivity increases during the green revolution in the second half of the 20th century were partly enabled by the industrial fixation of the once scarce nutrient via Haber-Bosch synthesis of ammonia (Erisman et al., 2008; Smil, 2002, 2004). Since then, human activities have altered the nitrogen cycle in such an unrivalled way, that the amount of N_r from anthropogenic sources entering terrestrial ecosystems outpaces the total of all natural sources (Boyer et al., 2004; Galloway et al., 2008; Vitousek et al., 1997). Agriculture is by far the most important anthropogenic driving force of the nitrogen cycle most prominently through fertilizer application, biological nitrogen fixation by soybeans, alfalfa and other legume crops, atmospheric deposition, animal manure and recycling of crop residues, where synthetic N compounds from industrial fertilizer represent the major input into the global crop sector (Smil, 1999; Socolow, 1999).

Large N_r losses within the agricultural system are associated with the inefficient conversion of plant-based to animal-based calories and proteins. Nitrogen conversion efficiencies are estimated to range between 5-8% for beef and 30-40% for milk (Smil, 2002). These inefficiencies are a direct result of the large biomass requirements to generate livestock products. Consequently, nitrogen inputs and losses occurring on cropland in the wake of feed cultivation can be attributed to the livestock sector. In the case of mineral fertilizer, feed production accounts for 20-25% of total application, resulting in global ammonia (NH_3) volatilization of 3.1 Mt NH_3-N (nitrogen in ammonia form) per year (Steinfeld et al., 2006). Moreover, a substantial amount of N_r is excreted as manure, where related losses depend on the extent that manure N_r is recycled as organic fertilizer and can be reused in crop production. However, a large share of manure N_r is lost through volatilisation and denitrification in manure management, and when applied on fields. Overall, livestock is considered responsible for 65% and 64% of anthropogenic nitrous oxide (N_2O) and NH_3 emissions (Steinfeld et al., 2006).

Once released to the environment, the same N_r particle can have multiple detrimental impacts at different stages of the nitrogen cascade, in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health (Galloway et al., 2003). Besides the already mentioned implications for water quality and pollution, the disruption of the nitrogen cycle implies increasing emissions of the greenhouse gas N_2O representing the fourth largest contributor to the natural greenhouse effect, after water vapour, carbon dioxide (CO_2) and methane (CH_4) (Socolow, 1999). Moreover, nitric oxide (NO) and nitrogen dioxide (NO_2), collectively called NO_x, control the formation of tropospheric ozone. Nitrogen gases (both ammonia and nitrogen oxides) are precursors of particular matter, that adversely affect human health and are involved in the appearance of acid rain and photochemical smog (Galloway et al., 2003; Socolow, 1999; Vitousek et al., 1997). Since the amount of N_r present in natural ecosystems is a decisive factor influencing species composition, productivity and carbon storage, modified N_r availability may shift system characteristics leading to a decline in biodiversity and to ecosystem simplification (Vitousek et al., 1997).

1.2.5. Climate

Between 1750 and 2011, 555 PgC were released to the atmosphere, of which 240 PgC accumulated in the atmosphere, 155 PgC were absorbed by oceans and another 160 PgC have been sequestered in the terrestrial biosphere (Stocker et al., 2013). Resulting CO_2 concentration of 391 ppm in 2011 (Stocker et al., 2013) is higher than at any time during the last 650 000 years (Siegenthaler et al., 2005). The concentration of CH_4 more than doubled since pre-industrial times (Spahni et al., 2005). A substantial part of GHG emissions which are attributed to the agricultural sector, like N_2O and CH_4 emissions from animal waste management systems, CH_4 emissions from enteric fermentation of ruminants and N_2O emissions from manure application to soils, can be associated with livestock farming. If also livestock induced emissions in other sectors are taken into account, e.g. caused by land use change, on farm fossil fuel, transport or processing of animal products, the total contribution of livestock is adding up to 18% of global anthropogenic GHG emissions (Steinfeld et al., 2006).

One third of GHG emissions attributable to livestock production stems from deforestation (Steinfeld et al., 2006). During the last years, carbon emissions from land use change accounted for approximately 12% of anthropogenic carbon emissions (Houghton et al., 2012), thus representing the second-largest source after fossil fuel combustion (van der Werf et al., 2009). Over the period 1750-2011, land use change even contributed 32% to total anthropogenic CO_2 emissions (Stocker et al., 2013). Historic land use change involved the loss of 25% primary forest over the last three centuries (Hurtt et al., 2011). However, the land system acted as a terrestrial carbon sink in recent decades, mainly owing to higher uptake of CO_2 by enhanced photosynthesis at higher CO_2 levels (CO_2 fertilisation effect) and nitrogen deposition (Pan et al., 2011; Stocker et al., 2013).

In view of the danger of climate change for agriculture and natural ecosystems, the potential of land to sequester carbon could become one of its vital functions for human societies besides food provision. The potential and cost-effectiveness of avoided deforestation to help mitigate climate change is widely acknowledged (Gullison et al., 2007; Kindermann et al., 2008; Soares-Filho et al., 2006). However, exclusion of non-forest carbon stocks such as soil carbon stored in grasslands from mitigation policies entails significant carbon leakage (Popp et al., 2014a). Cropland is typically less capable of storing soil C than grasslands, since grasslands have a high root turnover and substantial soil organic carbon stocks due to permanent vegetation cover (Don et al., 2011). Moreover, optimally grazed land performs better regarding its capacity to sequester carbon than overgrazed or ungrazed land (Conant et al., 2001; Conant and Paustian, 2002; Liebig et al., 2005; Smith et al., 2008). The annual carbon sequestration potential related to the restoration of global degraded rangelands is estimated to be 45 Tg C/yr, where highest potentials are suggested for Africa and Latin America (Conant and Paustian, 2002). Due to the vast areas involved in grazing systems, their management has a considerable global potential to alter fluxes of especially CO_2, but also of other GHGs (Smith et al., 2008).

1.3. The future of livestock production: dynamics of demand and supply

Livestock production simultaneously affects a wide range of natural resources, that must carefully be balanced in view of increasing scarcity of these resources, of the opportunities and constraints that they represent for other sectors and activities, and expected future development of food demand (Steinfeld et al., 2006). The different components of the livestock-environment nexus are not isolated, but linked at various stages. Some impacts are correlated and could simultaneously be tackled, like deforestation and CO_2 emissions, creating win-win situations for environmental protection. Some constellations are likely to generate trade-offs, such as the impacts and benefits centred on the utilization of pastures in livestock farming. While even today's level of environmental degradation attributable to livestock farming is critical, global demand for meat, milk and eggs is expected to continue growing, driven by population growth, increasing incomes, and urbanization. Measures aiming at more sustainable food supply and consumption patterns should bridge the gap between demand and supply-side dynamics of the livestock sector and account for many large-scale processes such as globalization, technological change, lifestyles, population growth and climate change.

1.3.1. Trends in food demand and dietary patterns

Shaped partially by factors outside agriculture, the livestock sector is subject to a wide-ranging transformation (Herrero et al., 2009, 2015; Steinfeld et al., 2006; Thornton, 2010). Human population, as one of the basic divers, continues to increase, but growth rates are slowing down since the peak in the late 1960s (United Nations, 2011). Although population growth is expected to further decline, world population is likely to reach 9 billion people in 2050, where the majority of growth will occur in developing countries (Alexandratos et al., 2012). Over the last five decades world population doubled, while demand for agricultural products approximately tripled in the same period (FAOSTAT, 2016), due to an increase in per-capita food demand driven by factors such as income, age structure, food prices, openness to global markets and urbanization (Drewnowski and Popkin, 1997; Popkin, 1993).

Since per-capita income is projected to grow substantially, also per-capita food demand will continue to rise, with projected levels in 2050 about twice the current level (Alexandratos et al., 2012). High levels of food demand as reported in many developed countries surpass plausible daily per-capita intake which resides between 2000 and 2300 kilocalories (Smil, 2000). Thus, high per-capita food demand is only partly a result of imbalanced diets and also a function of higher food waste at household level (Bodirsky et al., 2015), as 30-40% of purchased food items are estimated to be discarded in developed countries (Godfray et al., 2010; Gustavsson et al., 2011). However, daily caloric intake is often higher than recommendations in developed countries, together with low physical activity increasing health risks, most prominently from cardio-vascular diseases, diabetes, cancer and musculoskeletal disorders (WHO, 2013). On the other hand, malnutrition is still a prevailing problem, with 795 million people suffering from hunger and undernourishment in developing regions (FAO, 2015).

For understanding future demand-side dynamics of the livestock sector, another process connected to similar factors like increasing incomes, urbanization and changing lifestyles is just as important as rising per-capita food demand, namely the growing share of livestock products in diets (Bodirsky et al., 2015; Drewnowski and Popkin, 1997; Steinfeld et al., 2006; Thornton and Herrero, 2010). While there is still a large discrepancy between consumption of livestock products in developed and developing countries, the latter are currently undergoing a similar transition of dietary patterns as historically observed in many OECD countries (Gerbens-Leenes et al., 2010; Pingali, 2007). Thus, global livestock production is projected to grow faster than cereal production, mainly driven by the transition of food consumption patterns towards western diets in developing countries that geographically coincides with population growth and increase in per-capita food demand (Alexandratos et al., 2012; Valin et al., 2014a). While until the beginning of the 21st century, total demand for livestock products of all developing countries was equal to the demand of developed countries, this ratio is projected to change, such that livestock consumption in the developing world will be twice the consumption in the developed world in 2050 (Rosegrant et al., 2009), entailing a gross increase in meat and milk demand by 70-80% (Herrero et al., 2015). Nonetheless, per-capita consumption of livestock products in developing countries will still be significantly lower than Western levels (Herrero et al., 2009).

1.3.2. Livestock system dynamics

In the past, growing population, increasing food demand and dietary transitions triggered innovation in machinery, biology and chemistry, resulting in the intensification of agriculture (Steinfeld et al., 2006; Steinfeld and Gerber, 2010). At present, however, there is still a huge heterogeneity of livestock production systems and related productivity levels, in various economic settings and agroecological zones (Herrero et al., 2013, 2015).

Subsistence and low-input farming occurs in places, where population density and the share of animal-based calories in diets are low. Despite the minor contribution of pastoral systems to global meat and milk production, they involve large areas. On African rangelands alone, 14% of global cattle and 21% of sheep and goats are reared, the livelihoods of more than half of the around 30-40 million pastoralists worldwide being dependent on these resources and animals (Swallow and Bromley, 1995). According to several authors, increases in per-capita intake of animal products as well as growing population and hence population density will imply structural and social changes like fragmentation of rangelands and a transition of pastoralism to sedentary agricultural practices and way of life, resulting in the evolution of pastoral to agro-pastoral and of agro-pastoral to mixed crop/livestock systems of varying intensification levels (Baltenweck et al., 2003; Herrero et al., 2008, 2009; Hobbs et al., 2008; Reid et al., 2004, 2005).

Mixed crop-livestock systems of low to medium productivity levels generate the majority of livestock products in developing regions (75% of milk and 60% of meat), while simultaneously supplying almost half of the global cereal harvest (Herrero et al., 2010). Moreover, two-thirds of the world population is geographically related to these systems, where also an important share of future population growth will take place. Mixed systems allow for the integration of crop and livestock enterprises at different stages on the farm, such as use of manure to fertilize crops, crop residues to feed livestock, and animals to provide draft power to cultivate cropland (Herrero et al., 2010). Benefits arise from diversification of economic activities, buffering against weather-related risks, and nutrient recycling. However, pressures from population growth and rising food demand on the high-potential, intensively managed land in developing regions, e.g. in South Asia an East African highlands, are high, resulting in resource and biomass scarcity and problems to satisfy feed demand of animals (Herrero et al., 2010; Lal, 2004).

Market-oriented production systems are disposed to specialise and produce high-value commodities, where a shift to industrial and landless systems is likely to occur especially in the case of monogastric livestock production and high opportunity costs of land (Herrero et al., 2009; Naylor et al., 2005). Accordingly, 75% of global pork and poultry production takes place in industrial systems (Herrero et al., 2015), that are also projected to account for the lion's share of future increase in meat production (Herrero et al., 2009; Steinfeld et al., 2006). While the transition towards more intensive mixed crop-livestock systems in developing regions could entail synergies with regard to resource efficiency, improved food security and livelihoods of poor farmers (Herrero et al., 2009, 2010; Steinfeld et al., 2006), there is debate about the disadvantages of highly intensive production technologies and large-scale industrial operations involving pollution of terrestrial as well as aquatic ecosystems through excessive nitrogen, pesticides and pathogens, and the loss of biodiversity (Herrero et al., 2009; Lemaire et al., 2005, 2014).

Besides the socio-economic context in which livestock production systems evolve, they also substantially differ in feed use and generally in the type of resources they claim (Herrero et al., 2013; Steinfeld et al., 2006). Mixed crop-livestock systems often perform better regarding feed conversion than extensive systems and are relatively resource-efficient, as they can utilize residues from crop production as livestock feed and efficiently recycle nutrients from manure. However, regional differences in feed conversion efficiencies are substantial (Bouwman et al., 2005; Herrero et al., 2013; Wirsenius, 2000; Wirsenius et al., 2010). In contrast, landless industrial systems are very efficient regarding biomass requirements per product, but the higher nutrient density of feed entails a large contribution of crops to feed rations and related impacts of cropland feed production, such as irrigation, pesticides, lower carbon sequestration in managed land and newly fixed nitrogen inputs into the agricultural system. In general, agroecology and intensification level largely determine feed conversion efficiency and composition of feed rations, where a higher quality of feed components goes hand in hand with better feed conversion (Herrero et al., 2013).

Given the huge differences in feed sources and feed conversion efficiencies between regions and production systems, there is a large potential to be tapped to improve overall resource use of agriculture by a transformation of livestock systems and productivity gains in the livestock sector.

1.3.3. Livestock in a changing climate

Livestock production does not only take place under changing socio-economic conditions, but also in the context of a changing climate. Consequences for livestock production are twofold. On the one hand, climate change will involve impacts on the natural resource base of livestock production like water resources as well as crop and rangeland productivity (Ghahramani and Moore, 2013; Thornton and Gerber, 2010). On the other hand, a changing climate will directly affect animals and influence the distribution and severity of livestock diseases (Godber and Wall, 2014; Perry et al., 2013; Thornton and Gerber, 2010), animal health and welfare as well as reproductive performance and livestock productivity (Lara and Rostagno, 2013; Nardone et al., 2010; Thornton et al., 2009). Impaired conditions for livestock farming need to be counterbalanced by adequate adaptation strategies that also have to be evaluated regarding their implications for food security and climate change mitigation (Herrero et al., 2015). While recent advances improved our understanding of several distinct channels of climate change impacts on livestock production, most integrated and large-scale assessments of climate change impacts on agriculture so far focus on the crop sector (Leclère et al., 2014; Nelson et al., 2014; Schlenker and Lobell, 2010). There are still large gaps in knowledge of how different livestock production systems are affected by climate change and how they could contribute to climate proofing agriculture.

Several studies suggest multi-gas mitigation strategies applying price-based policy instruments like emission trading schemes as cost-efficient ways to meet climate protection targets (Lucas et al., 2007; van Vuuren et al., 2006). Since 37% of CH_4 and 65% of N_2O emissions can be attributed to livestock production, targeting non-CO_2 greenhouse gases makes the agricultural and especially the livestock sector an important lever of mitigation efforts. Furthermore, there is an increasing concern that the agreed climate stabilization targets cannot be met without including the land system (Popp et al., 2014a; Wise et al., 2009). Mitigation schemes that only control the energy and industrial sector tend to create additional emissions from terrestrial sources, e.g. through incentives to increase bioenergy

(Crutzen et al., 2008; Fargione et al., 2008; Searchinger et al., 2008). Bringing land centre stage for climate protection will alter opportunity costs of the vast land areas associated with livestock farming.

Due to the substantial climate burden of livestock production, efforts to limit global temperature increase to less than 2°C above preindustrial level by the end of this century will likely have repercussions on the livestock sector. Being simultaneously confronted with impacts of a changing climate, the livestock sector must further evolve to respond to adaptation and mitigation necessities. Thereby, the impacts of both feed composition and the share of livestock products in human diets on the whole agricultural system are of great importance, influencing the level of agricultural biomass production and the ratio between cropland and pasture.

2. Research questions

While already today's magnitude of the environmental hoofprint gives cause to concern, the livestock sector will likely experience further growth and undergo far-reaching transformation, as outlined in the background section. The scientific objective of this thesis is to fill gaps in our understanding of the current environmental footprint of animal agriculture, to gain insights into environmental consequences of alternative future demand- and supply-side developments in the livestock sector and to identify strategies to attenuate resource use and interference with biochemical cycles. The here presented analysis investigates interactions between animal agriculture and the environment in the context of global change processes like population growth, dietary transition and increasing per-capita food demand with rising income, agricultural innovation, and climate change impacts on agriculture.

Thus, this thesis is guided by the following overarching research question:

How will future livestock production interact with the environment in the context of a changing world and how do dietary choices and transitions in livestock production systems affect agricultural resource use and environmental externalities?

The following chapters II-V, which represent the main part of the thesis, address different aspects of this overarching question.

How do transitions in current livestock production systems affect agricultural land use and the balance between resource requirements and availability in a changing climate?
(Chapter II)

Recent advances in disaggregating data on biomass use, production and feed efficiency of the global livestock sector reveal huge discrepancies in regional feed conversion and feed composition across different livestock production systems even for the same product (Herrero et al., 2013). As a first step, this thesis aims at understanding the transformative potential of shifts between current livestock production systems to improve overall resource use of agriculture, especially in view of associated agricultural land requirements and productions costs. Moreover, the thesis investigates how structural changes in the livestock sector could represent an efficient strategy to adapt livestock production to climate change impacts on the natural resource base. Shifts in livestock production systems do not only alter overall feed and land use, but also the type of feed and land that is used to produce animal products, i.e. concentrates from cropland, grazed biomass from pastures or crop residues and food industry by-products as residuals or side-products of the food supply chain. Both mechanisms – changes in feed efficiency and feed composition - can absorb detrimental impacts of climate change on plant production, where the latter can exploit the potentially diverging impacts of climate change on different crops as well as on cropland and pasture productivity.

What is the current contribution of livestock production to agricultural resource use and environmental externalities?
(Chapters III and IV)

While considerable progress has been made towards quantification of environmental externalities related to animal agriculture over the last decade, there are still some areas where the magnitude of livestock related impacts is rather uncertain even for the present state and merits further analysis. This thesis provides new estimates of agricultural green and blue water consumption and N_r flows attributable to livestock production. Detailed cropland and pasture N_r budgets are created including N_r inputs from manure, crop residues left in the field, biological N_r fixation, soil organic matter loss, atmospheric deposition, seeds and inorganic fertilizer. N_r flows are further tracked upstream towards the processing sector, the livestock sector and final consumption to unmask the low N_r efficiency within agriculture and especially the role of livestock production for the agricultural nitrogen cycle. For the quantification of water consumption related to livestock feed production, either stemming from naturally infiltrated rainwater (green water) or from irrigation water withdrawn from rivers, lakes and aquifers (blue water), detailed estimates of feed use are combined with spatially explicit data on land use and cropping patterns, area quipped for irrigation, water availability and crop water demand for rainfed and irrigated crops.

How do resource use and environmental impacts of agriculture evolve under different scenarios of livestock production?
(Chapters II, III, IV and V)

The contribution of animal farming to current agricultural resource use is substantial. Understanding impacts of possible future developments of the livestock sector on the agricultural system and the environment is pivotal to identify key sustainability trade-offs and measures to mitigate environmental externalities of food production. At the demand side, population growth and a continuation of the livestock revolution in developing countries are likely to further exacerbate environmental impacts of livestock production. At the supply side, economic growth and increasing population densities might trigger structural changes in the livestock sector, entailing changes in livestock production systems and the level of intensification. Across the different studies presented in chapters II, III, IV and V, this thesis investigates several possible scenarios of future livestock production and assesses their environmental consequences in terms of agricultural biomass production, land use and land use change (e.g. deforestation), carbon emissions from land use change, nitrogen flows, N_2O emissions as well as green and blue water consumption.

How can changes in livestock productivity alter the environmental footprint of agriculture?
(Chapters II, IV and V)

Between the 1960s and the turn of the millennium, meat and milk production increased by 245% and 70%, respectively, while at the same time arable land used for feed production increased by 30% and grazing land by less than 10% (Steinfeld and Gerber, 2010). Consequently, it is impossible to scale up resource use and environmental impacts of livestock production linearly with increasing consumption of livestock commodities. Quite the contrary, the role of productivity gains in the livestock sector to attenuate critical sustainability issues merits particular attention. Thereby, this thesis does not only investigate the potential of shifts between current livestock production systems to alter agricultural resource requirements, but in a second step progresses to a more comprehensive analysis of the relationship between livestock productivity, feed efficiency and composition, facilitating the assessment of productivity gains beyond the level of current systems. Within an integrated framework that considers major dynamics of the agricultural sector like land expansion, improved management in the crop sector, expansion of irrigation and re-allocation of production via trade dynamics, impacts of different livestock productivity pathways on environmental externalities are studied, e.g. representing a catch-up of low productive systems to higher productivity levels or moderate productivity reductions in intensive systems, since recent research raises concerns about downsides of highly intensive livestock operations like conflicts with animal welfare and pollution (Carvalho et al., 2010; Franzluebbers et al., 2014; Lemaire et al., 2014).

What is the potential of dietary choices to attenuate environmental externalities of food production?
(Chapters IV and V)

Current diets vary greatly regarding the contribution of animal-based food. At the global level, livestock products provide 18% of calories (39% of proteins), while in many developed countries almost 30% of calories (60% of proteins) stem from meat, milk, eggs and fish (FAOSTAT, 2016), thus considerably exceeding dietary recommendation (Springmann et al., 2016). However, many regions' populations still experience malnutrition and nutrient deficits. With rising incomes, per-capita intake of livestock products is expected to increase substantially. On the other hand, environmental and ethical concerns in developed regions could lead to a decline in the consumption of animal-based products (Fox and Ward, 2008). Due to the low resource-use efficiency of livestock production upstream in the food supply chain, shifting dietary preferences from animal- to plant-based calories in affluent regions could simultaneously reduce several critical environmental externalities of food production. This thesis explores the potential of reducing the consumption of livestock products in developed regions to attenuate the environmental footprint of agriculture, where special attention is given to impacts on agricultural biomass production, land and carbon dynamics, green and blue water consumption and water scarcity.

What is the role of pastures for sustainable livestock futures?
(Chapters II, III, IV and V)

Pastures provide around 50% of feed use of the global livestock population (Herrero et al., 2013; Steinfeld et al., 2006). While grazing pertains to vast land areas, it requires little additional inputs like irrigation and fertilization and could possibly contribute to soil carbon sequestration on agricultural land (Conant et al., 2001; Conant and Paustian, 2002). The future development of grazing is very uncertain and projections of pasture area until the middle of this century substantially differ across models and scenarios (Popp et al., 2017; Schmitz et al., 2014). While grasslands outperform cropland in view of biodiversity and carbon sequestration, they are at the epicentre of various land-use change processes (Herrero et al., 2013). Conversion of forests into grassland is a primary cause of deforestation, but pastures can also be converted into cropland, thus diverting pressures from pristine ecosystems. Across different chapters of this thesis, alternative future developments of livestock production are analysed regarding the role of pasture to provide feed, counterbalance climate change impacts on crops and grasses, drive land and carbon dynamics and attenuate or exacerbate pressure on pristine ecosystems and water resources.

3. Methodology

3.1. Research approach

The future of livestock production will evolve in the interplay between human and natural systems, between broad scale drivers of human development and spatially explicit resource constraints for agricultural production. Accordingly, an analysis of environmental consequences arising from alternative future demand- and supply-side trends in the livestock sector has to bridge scales and disciplines. The methodology of this thesis reflects the interdisciplinary nature of its scientific objective and is built upon the concept of economic land-use modelling that combines the strengths of two classes of models, process-based biophysical models and agro-economic market models.

As outlined in the above sections, agricultural and, more general, economic activities of human societies in the 'Anthropocene' represent a large interference in major biochemical cycles, thereby resembling the great forces of nature (Rockström et al., 2009; Steffen et al., 2007). Thus, economic activities can in a broader sense be interpreted as physical, biological and chemical processes (Røpke, 2004). Biophysical models have to be extended by implementing anthropogenic drivers of biophysical processes to facilitate long-term assessments of water, nitrogen and carbon cycles and the exploration of sustainable futures (Verburg et al., 2016).

On the other hand, agro-economic models like general equilibrium models often lack the spatial representation of resource endowment and biophysical constraints for agricultural production to explore long-term trends and capture feedbacks between socio-economic drivers and the natural resource base of agriculture. Spatially explicit characteristics of land like soil properties, geography, accessibility, water availability and climate do not only determine its economic value in view of scarcity and demand, but also associated environmental implications resulting from land use. Carbon emissions from land conversion depend on the spatially heterogeneous amount of soil, litter and vegetation carbon previously stored in converted land. For instance, carbon storage in tropical forests is more than 50% higher than in boreal forests (Van Kooten, 2011). Similarly, cropping is less likely to disturb hydrological processes and tap into environmental flow requirements of aquatic ecosystems in places where water is abundant, either in the form of green precipitation water or blue freshwater, than in water-scarce locations (Bonsch et al., 2015).

Spatially explicit economic land use models emerged as a model family fusing biophysical and agro-economic models into an integrated modelling framework, thus fostering a high level of integration between disciplinary approaches of natural and social sciences. As will be described in the following subsection, the spatially explicit economic land and water use model MAgPIE (Model of Agricultural Production and its Impact on the Environment) (Bodirsky et al., 2014; Lotze-Campen et al., 2008; Popp et al., 2014a, 2017; Stevanović et al., 2016) is well suited to address the research question and to investigate future dynamics in coupled human-natural systems. To explore possible environmental externalities of future livestock production, scenarios are developed and assessed that include important drivers of socio-economic development and agricultural production and vary demand- and supply-side assumptions with regard to the livestock sector.

3.2. Modelling framework

MAgPIE represents key human-environment interactions in the agricultural sector by combining socio-economic regional information with spatially explicit data on biophysical constraints provided by the Lund-Potsdam-Jena dynamic global vegetation model with managed Land (LPJmL) (Bondeau et al., 2007; Müller and Robertson, 2014; Rost et al., 2008). Both models are developed and managed by the Potsdam Institute for Climate Impact Research (PIK) and represent, together with the macroeconomic and energy model REMIND (Klein et al., 2014; Luderer et al., 2013), key elements of the Potsdam Integrated Assessment Modelling (PIAM) framework, covering the energy-climate-land-water nexus.

The MAgPIE model simulates long-term developments of the agricultural sector in a recursive dynamic mode by minimizing a nonlinear global objective function for each time step. It integrates regional socio-economic drivers and constraints such as income and resulting per-capita demand for different agricultural commodities, population, trade restrictions and production costs with spatially explicit data on potential crop yields, pasture productivity, crop water demand for irrigated and rainfed production as well as land and water availability into an economic decision making process, thereby fulfilling demand for food, feed, seeds and materials.

The exogenous calculations of food demand represent the dynamics of the dietary transition with increasing economic development. They are based on an econometric regression model for national caloric intake per-capita and depend on income and population scenarios (Bodirsky et al., 2015; Valin et al., 2014b). Material demand is assumed to grow proportionally to food demand. Regional feed demand depends on livestock production quantities and regional system-specific feed baskets that evolve with the level of intensification (chapters II-V of this thesis).

Endogenous trade dynamics control the allocation of global demand for agricultural commodities to the supply regions, where exogenous trade restrictions define the proportion of agricultural goods that can, on top of historical trade patterns, traded according to comparative advantages (Schmitz et al., 2012). Technological change, which increases crop yields and pasture productivity, is implemented as an endogenous process, where the level of investments required for achieving a certain yield growth depends on the current technology level (Dietrich et al., 2014). This dynamic representation of technological innovation allows for simulating feedbacks from increasing resource scarcity on management intensity and efforts to invest into productivity gains in the agricultural sector, processes that have been already observed in the past (Steinfeld et al., 2006; Steinfeld and Gerber, 2010).

Competition for land is explicitly addressed for cropland, pasture, forest (including forestry), and other land (other natural vegetation such as savannahs and shrubland as well as abandoned agricultural land). The suitability of land for crop cultivation further constrains the conversion of natural vegetation or pastures to cropland and is primarily determined using crop yields from LPJmL. Additionally, cropping can only occur on land that is at least marginally suitable for rainfed crop production with regard to climate, topography and soil type according to the Global Agro-Ecological Assessment (GAEZ) methodology on land suitability (Fischer et al., 2002; Krause et al., 2013; van Velthuizen et al., 2007). In response to production costs and biophysical constraints, MAgPIE optimizes the spatial distribution of crops and pasture within current agricultural land as well as the balance between land expansion, agricultural intensification, irrigation and trade.

MAgPIE is applied for a broad spectrum of research questions like climate change mitigation options (Humpenöder et al., 2014; Popp et al., 2011, 2014b; Stevanović et al., 2017), nutrient cycles (Bodirsky et al., 2012, 2014), bioenergy (Bonsch et al., 2014; Lotze-Campen et al., 2014), climate change impacts (Stevanović et al., 2017; Weindl et al., 2015), water scarcity (Bonsch et al., 2015; Schmitz et al., 2013), and trade (Biewald et al., 2014; Schmitz et al., 2012). In combination with the energy–economy–climate model REMIND (Luderer et al., 2013), the REMIND/MAgPIE framework (Popp et al., 2011) was amongst the Integrated Assessment Models (IAMs) that were applied for the translation of the narratives of the Socio-Economic Pathways (SSPs) into quantitative projections and for the systematic interpretation of the different SSPs in terms of possible land-use (Popp et al., 2017) and energy futures (Bauer et al., 2017).

3.3. Livestock in MAgPIE

Historical developments suggest interdependencies between the rising food demand of a growing and increasingly wealthy human population and the trend towards intensification in animal agriculture. Over the past half-century, livestock feed demand increased by 108%, arable land for feed crops by 30% and pasture by 10%, while animal calorie production more than tripled, which is mainly attributable to improved and more resource-efficient production methods (Davis et al., 2015; Herrero et al., 2010; Steinfeld and Gerber, 2010).

In consequence, the environmental burden of future livestock production is likely to be subject to innovation, productivity increases and management in livestock production systems. To facilitate the analysis of the role of productivity gains in the livestock sector for resource use and the environmental footprint of agriculture, this thesis proceeds in two steps:

Firstly, acknowledging current heterogeneity of livestock production systems, chapter II investigates resource implications of a shift in regional livestock production systems, involving changes in feed efficiency and composition. For this aim, the simplistic representation of livestock production in the early phase of MAgPIE model development was replaced by the detailed dataset on livestock production systems by Herrero et al. (2013). Chapter II highlights the magnitude of differences in land use dynamics and especially deforestation until 2050 stemming from variations in current systems. However, structural changes in current regional systems are unlikely to suffice for the description of possible productivity gains in the next decades, since variations of livestock productivity within the same livestock production system and agroecological zone strongly vary across regions and historical developments in some places demonstrate the large magnitude of possible productivity gains even within one or two decades (e.g. China for beef).

In a second step, a comprehensive method was therefore developed to establish a relationship between livestock productivity, feed efficiency and feed composition that can be used to design livestock futures that are consistent with both historical livestock productivity developments and scenario storylines (chapters IV and V). The implementation of the livestock sector into MAgPIE was realized as part of this thesis and is a prerequisite to achieve its scientific aims. A comprehensive description of the model development can be found in chapters II, III and IV.

4. Structure of the thesis

The main part of this cumulative thesis consists of four scientific articles that have been published (chapters II and III) or are currently under review (chapters IV and V). The articles are the result of a scientific cooperation between various authors and are based on the joint endeavour to develop and manage a large model like MAgPIE, which is always a group effort. While representing self-contained studies with own layout and references, the four articles are connected by the common research objective and methodological approach of the thesis and address different aspects of the overarching research question as outlined in section 2 of this chapter. Chapter VI synthesises results and key findings across the individual chapters and provides an outlook on further research and model development.

Chapter II explores the potential of a transition between current livestock production systems to transform biomass flows in agriculture, improve overall resource use and counterbalance detrimental impacts of climate change on the natural resource base of livestock farming. For this aim, the simplistic representation of livestock production in the early phase of MAgPIE model development was replaced by a detailed representation of livestock production systems, which were parametrised according to the dataset published by Herrero et al. (2013) describing the huge heterogeneity of feed conversion efficiency and resource use inherent in livestock production at present.

Chapter III provides a comprehensive description of the current agricultural N_r cycle and presents four long-term scenarios based on the storylines of the Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000). These scenarios combine different assumptions on e.g. population growth, food demand and the share of animal-based calories in diets, livestock production intensification and animal waste management. For this study, MAgPIE was extended by several features to describe the dynamics of the N_r cycle, such as the production and different uses of crop residues and conversion byproducts as well as a detailed representation of agricultural N_r flows. Special attention is given to the role of the livestock sector within the agricultural N_r cycle. For this purpose, the implementation of livestock feed production was improved, differentiating feed that is harvested on cropland, biomass from pastures and various residues generated along the food supply chain, such as crop residues, conversion byproducts from food processing and food waste.

Chapter IV estimates current and future levels of agricultural blue and green water consumption attributable to livestock production and assesses potentials of changing dietary preferences and shifts in livestock production systems to decrease agricultural water requirements and attenuate water scarcity. To explore implications of different livestock productivity trend on water use, the implementation of livestock production in MAgPIE was extended for this study. Livestock feed baskets were calculated at the country scale and a comprehensive method was developed to establish the relationship between livestock productivity, feed efficiency and feed composition. To account for spatial heterogeneity, the non-linear regression models for feed composition also consider aggregated climate indicators based Koeppen-Geiger climate zones. The extended livestock implementation is presented in detail in the Supplementary information (SI appendix) of this chapter.

Chapter V quantifies impacts of changing human diets and livestock productivity on land dynamics and carbon emissions from land conversion processes. The study specifically addresses implications of future livestock production on the interplay between different managed and unmanaged land types and related trade-offs in terms of carbon losses from vegetation, litter and soils. The analysis of land and carbon dynamics under different livestock futures is based on the same model set-up as chapter IV, thereby representing a complementary assessment of environmental externalities attributable to livestock production.

Chapter VII synthesizes results of the individual chapters in view of the research questions and summarizes key findings of the doctoral thesis. Finally, an outlook on future research and model development is given that addresses three main pillars: detailed representation of pasture management and grazing intensities, endogenisation of livestock sector transformations (demand- and supply-side) and a spatially explicit implementation of livestock in MAgPIE.

Chapter II: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture

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Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture

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Abstract

Livestock farming is the world's largest land use sector and utilizes around 60% of the global biomass harvest. Over the coming decades, climate change will affect the natural resource base of livestock production, especially the productivity of rangeland and feed crops. Based on a comprehensive impact modeling chain, we assess implications of different climate projections for agricultural production costs and land use change and explore the effectiveness of livestock system transitions as an adaptation strategy. Simulated climate impacts on crop yields and rangeland productivity generate adaptation costs amounting to 3% of total agricultural production costs in 2045 (i.e. 145 billion US$). Shifts in livestock production towards mixed crop-livestock systems represent a resource- and cost-efficient adaptation option, reducing agricultural adaptation costs to 0.3% of total production costs and simultaneously abating deforestation by about 76 million ha globally. The relatively positive climate impacts on grass yields compared with crop yields favor grazing systems inter alia in South Asia and North America. Incomplete transitions in production systems already have a strong adaptive and cost reducing effect: a 50% shift to mixed systems lowers agricultural adaptation costs to 0.8%. General responses of production costs to system transitions are robust across different global climate and crop models as well as regarding assumptions on CO_2 fertilization, but simulated values show a large variation. In the face of these uncertainties, public policy support for transforming livestock production systems provides an important lever to improve agricultural resource management and lower adaptation costs, possibly even contributing to emission reduction.

1. Introduction

Livestock production constitutes a significant interference with many Earth system processes. In the courses of providing on average 17% of food calories and more than a third of protein to human diets (Herrero *et al* 2009), livestock is consuming almost 60% of the global biomass harvest (Krausmann *et al* 2008), using around 30% of agricultural water withdrawals (Peden *et al* 2007, Mekonnen and Hoekstra 2010), and dominating the agricultural nitrogen cycle (Bodirsky *et al* 2012, 2014, Bouwman *et al* 2013). Moreover, the livestock sector is held responsible for about 12%–18% of all anthropogenic greenhouse gas (GHG) emissions (Steinfeld *et al* 2006, Westhoek *et al* 2011). While being associated with many critical environmental impacts, livestock reduces vulnerability to environmental risks for 600 million poor smallholder farmers (Steinfeld *et al* 2006, Thornton and Herrero 2010) and provides livelihoods as well as many other services beyond food production such as traction and nutrients (Steinfeld *et al* 2006, Herrero *et al* 2009). Especially for many poor and undernourished people in the developing world, livestock products are crucial for protein supply.

Livestock is thus intertwined with many aspects of the challenge to sustainably feed a growing world population and achieve a balance between livelihoods, food security and the environment (Herrero and Thornton 2013). Being the world's largest user of land and biomass and at the same time an important risk management strategy for vulnerable communities (Herrero *et al* 2009), livestock is at the center of the discourse on climate change and agriculture. Recent work reveals large potentials to abate GHG emissions in the livestock sector, amongst others by reducing livestock product consumption (Stehfest *et al* 2009, Popp *et al* 2010), shifts in production systems and improved management (Thornton and Herrero 2010, Havlík *et al* 2013, 2014, Smith *et al* 2013, Valin *et al* 2013, Cohn *et al* 2014). However, impacts of climate change on the livestock sector have hitherto been analyzed in a comparably integrated approach only by Havlík *et al* (2015). As most studies on climate change impacts and agriculture so far have focussed on the crop sector (Schlenker and Lobell 2010, Müller *et al* 2011, Leclère *et al* 2014, Nelson *et al* 2014a), there are still large gaps in knowledge of how climate change could affect livestock production and how a transformation of livestock production systems (LPS) could contribute to a climate-smart agriculture.

There are several ways in which livestock production will be influenced by a changing climate, such as changes in the productivity of rangelands and yields of feed crops (Thornton and Gerber 2010, Ghahramani and Moore 2013). Moreover, heat stress directly impairs production (meat, milk and egg yield and quality) and reproductive performance as well as animal health and welfare (Thornton *et al* 2009, Nardone *et al* 2010, Gaughan 2012, Lara and Rostagno 2013). One key entry point into the complex livestock-climate-nexus is the substantial heterogeneity of feed conversion efficiencies (product output per feed input) across different LPS. Not only is the overall resource use intensity affected by shifts in LPS, but also the feed basket composition, i.e. concentrates from cropland, roughage from rangelands or crop residues as by-products (Herrero *et al* 2013). Both mechanisms can absorb detrimental impacts of climate change on the natural resources base, where the latter can exploit the potentially diverging impacts of climate change on different crops as well as on cropland and pasture productivity. At the same time, structural changes like a transition from grazing to mixed crop-livestock systems may also positively affect the resource footprint of livestock, deforestation rates and GHG emissions (Herrero *et al* 2010b, 2013, Havlík *et al* 2014).

In this study, we quantify the impacts of a changing climate on the agricultural sector and explore the adaptive potential of LPS transitions, based on a comprehensive impact modeling chain. Hereby, we analyze direct climate impacts on cropland and pasture productivity as well as secondary impacts such as changes in land-use dynamics (i.e. deforestation) and agricultural production costs. By contrasting effects of different LPS transition pathways, we provide insights into how related changes in feed conversion efficiencies and feed baskets may buffer or amplify secondary climate impacts in the light of the changing availability of natural resources and identify regionally specific adaptation strategies in the livestock sector.

2. Methods and data

2.1. Modeling framework

We assess the biophysical response of agricultural crops and rangelands to a changing climate at a spatial resolution of 0.5 × 0.5 geographic degrees, using the Lund-Potsdam-Jena dynamic global vegetation model with managed Land (LPJmL) (Bondeau *et al* 2007, Rost *et al* 2008, Waha *et al* 2012, Müller and Robertson 2014). LPJmL simulates growth, production and phenology of 9 plant functional types (representing natural vegetation at the level of biomes (Sitch *et al* 2003)) and of 12 crop functional types (SI appendix, tables S3(a)–(f)) as well as managed grass, ensuring global balances of carbon and water fluxes and explicitly accounting for the photosynthesis pathway (C3 versus C4 plants). The photosynthetic processes are modeled according to Farquhar *et al* (1980) and Collatz *et al* (1992). Yield simulations are based on various process-based implementations as described in more detail by Bondeau *et al* (2007) and Waha *et al* (2012). Harvesting of crops occurs on completion of the phenological cycle (maturity), while grassland is harvested at least once a year (up to several times a year) as soon as the phenological leaf development is completed and a minimum above-ground biomass threshold of 100 gC/m^2 has been reached (see SI appendix for more details). The LPJmL model represents both C3 and C4 grasses, with distinct photosynthetic pathways (Sitch *et al* 2003). Up to annual mean temperatures of 15.5 °C, C3 grasses establish, at or above 15.5 °C C4 grasses establish, which also allows for mixed composition.

The impacts of climate change and shifts in LPS on agricultural land use and production costs are explored with the Model of Agricultural Production and its Impact on the Environment (MAgPIE) (Lotze-Campen *et al* 2008, Bodirsky *et al* 2012, 2014, Popp *et al* 2014, 2010), a spatially explicit global land-use allocation model. By minimizing a nonlinear global cost function for each time step, the model fulfils demand for food, feed and material for 10 world regions (table 1, figure S2). The model represents key human-environment interactions in the agricultural sector by combining socio-economic regional information with spatially explicit data on biophysical constraints provided by LPJmL (i.e. pasture productivity, crop yields under rainfed and irrigated conditions,

Table 1. Socio-economic regions in MAgPIE.

Regional acronyms	MAgPIE regions
AFR	Sub-Sahara Africa
CPA	Centrally Planned Asia (incl. China)
EUR	Europe (incl. Turkey)
FSU	Former Soviet Union
LAM	Latin America
MEA	Middle East and North Africa
NAM	North America
PAO	Pacific OECD (Australia, Japan and New Zealand)
PAS	Pacific Asia
SAS	South Asia (incl. India)

related irrigation water demand per crop, water availability) and land availability (Krause *et al* 2013). Region-specific costs associated with different farming activities are derived from the GTAP database (Narayanan and Walmsley 2008). In view of the involved production costs and resource availability, MAgPIE optimizes land use patterns and simulates major dynamics of the agricultural sector like land use change (including deforestation, abandonment of agricultural land and conversion between cropland and pastures), investments into research and development (R&D) and associated yield increases, interregional trade flows, and irrigation (see SI appendix for more details).

Livestock products are represented by six categories: beef, sheep and goat meat, pork, chicken, eggs, and milk. These commodities are produced in eight different LPS according to the updated International Livestock Research Institute/FAO classification (Robinson *et al* 2011, Herrero *et al* 2013): three rangeland-based systems (LG), and three mixed crop-livestock systems (MX), which are the aggregate of the mixed rainfed systems (MR) and mixed irrigated systems (MI) of the original FAO nomenclature, an industrial system, and a smallholder system. LG and MX systems are further differentiated by agroecological zones (arid and semiarid; humid and semihumid; tropical highlands and temperate). Pork, chicken, and eggs are only produced in industrial and smallholder systems, whereas ruminant meat and milk are mainly produced in rangeland-based and mixed systems. The parameterization of the different LPS, especially total feed efficiencies and the composition of feed baskets, relies on the dataset presented by Herrero *et al* (2013) and is consistent with FAO statistics regarding livestock production, animal numbers, and livestock productivity.

2.2. Scenario definition

The analysis presented here is based on the reference scenario of the International Assessment of Agricultural Science and Technology for Development (IAASTD) (McIntyre *et al* 2009) which was developed applying several models like the IMPACT agriculture-economy model (Rosegrant *et al* 2002) and the Integrated Model to Assess the Global Environment (IMAGE) (Bouwman *et al* 2006). The underlying climate patterns of the IAASTD scenario (SI appendix, figure S1) define our central climate scenario which is provided by the IMAGE group (van Vuuren *et al* 2007). Acknowledging the uncertainty involved in simulating future climate conditions, we test the sensitivity of our results to other climate projections for the A2 SRES scenario, based on 5 different general circulation models (GCMs) (i.e. CCSM3 (Collins *et al* 2006), ECHAM5 (Jungclaus *et al* 2006), ECHO-G (Min *et al* 2005), GFDL (Delworth *et al* 2006), and HadCM3 (Cox *et al* 1999); see SI appendix for more details).

Moreover, we address another important aspect of uncertainty: the effectiveness of CO_2 fertilization, i.e. the potential of atmospheric CO_2 to stimulate net photosynthesis in C3 plants by increasing the CO_2 concentration gradient between air and the leaf interior, and improved water use efficiency of all crops and grasses due to stomatal closure. Whether and how CO_2 fertilization is accounted for in global gridded crop models (GGCMs) substantially influences simulated climate impacts on agriculture (Rosenzweig *et al* 2013). Thus, we perform a sensitivity analysis by simulating yield responses over time both with the full CO_2 effect as implemented in LPJmL (i.e. direct CO_2 fertilization, indirect CO_2 fertilization via reduced stomatal conductance, no down-regulation or feedbacks via nutrient dynamics, no effects on pests and diseases) and with static atmospheric CO_2 concentrations of the year 2000 (370 ppm) for all scenarios and climate projections. Due to large variations of simulated climate impacts on crop yields among GGCMs (Asseng *et al* 2013, Rosenzweig *et al* 2013, Müller and Robertson 2014), we also test the sensitivity of our results to the choice of crop growth model by using alternative crop yield simulations derived by EPIC (Williams 1995, Izaurralde *et al* 2006) and pDSSAT (Jones *et al* 2003).

Throughout the paper, the base year 2005 and the final year 2045 of the simulation period represent 10-year averages, in terms of climate and yield changes as well as all other outputs.

To explore impacts of climate change on agriculture and the adaptive potential of two different LPS transitions, we conduct a scenario analysis with MAgPIE (see table 2 for an overview of the scenario setting). In all scenarios, regional food and material demand as well as international trade in agricultural commodities is harmonized with the reference case of the IAASTD (McIntyre *et al* 2009) (SI appendix, table S1). In the baseline, climate conditions are kept constant at 2005 levels and the regional composition of LPS is parametrized over time following projected rates of growth in different LPS 2000–2030 according to Herrero *et al* (2010a) which are also based on

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Table 2. Overview of the scenario setting.

Scenario	Description
Baseline	World population increases to 8.9 billion people and average per capita food demand to 3 447 kcal per day in 2045, consistent with the reference case of the IAASTD (McIntyre *et al* 2009). The regional composition of LPS changes gradually over time according to Herrero *et al* (2010a). Climate conditions are kept constant at 2005 levels.
Climate_impact	In addition to 'Baseline' conditions, climate effects on yields, based on the IAASTD climate scenario (van Vuuren *et al* 2007), are taken into account. Global mean temperature increases by 1.1 °C from 2005 to 2045.
Shift_to_rangeland	In addition to 'Climate_impact' conditions, production of ruminant meat and milk is gradually shifted towards rangeland-based systems, with full convergence until 2045.
Shift_to_mixed	In addition to 'Climate_impact' conditions, production of ruminant meat and milk is gradually shifted towards mixed systems, with full convergence until 2045.

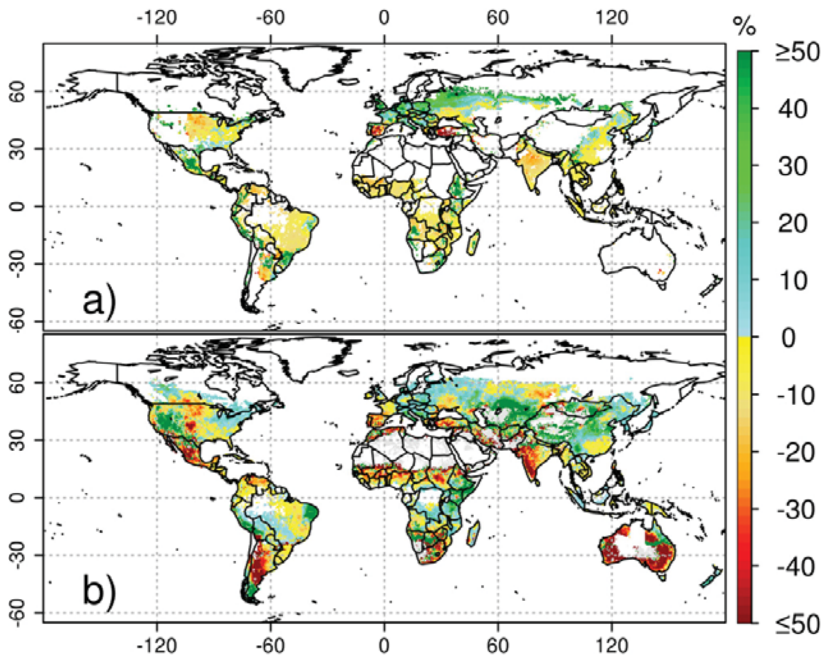

Figure 1. Climate impacts on maize yields (a) and rangeland productivity (b) by 2045 for the IAASTD climate scenario (percent change from 2005, simulated with the LPJmL model, no CO_2 effect; for maize: no adaptation in cropping period or varieties, area-weighted mean of rain-fed and irrigated; for rangeland: no nutrient limitations, adaptive harvest cycles). Results with full CO_2 effect are given in figure S7 (SI appendix).

the reference scenario of the IAASTD. Adaptation costs are calculated as the difference in total agricultural production costs between the baseline run and scenarios accounting for climate change impacts. These costs reflect the sum of additional expenses needed to counterbalance the changes in land productivity, i.e. higher investments into R&D and land conversion, and increasing factor inputs. The LPS transition scenarios described below focus on shifts in ruminant meat and milk production, since ruminants account for the largest share in agricultural land use and are crucial for land use changes between cropland and rangeland. We design stylized LPS transition scenarios with full system convergence until 2045 to unravel their complete potential to alter agricultural land use and production costs, especially in comparison to climate change impacts.

3. Results

3.1. Climate impacts on crop and rangeland productivity

According to the IAASTD climate scenario, large parts of SAS, AFR, NAM and FSU become warmer by 1.8 °C or more (SI appendix, figure S1). Precipitation declines by 25%–50% in parts of MEA, AFR, SAS, PAO, and LAM. Many other regions, especially in the Northern Hemisphere, experience an increase in precipitation. Under constant CO_2 levels, yields of maize, one of the most important feed crops, tend to increase in most temperate zones, owing to alleviated temperature limitations (figure 1(a)). However, declining yields are simulated in parts of NAM, FSU, and CPA, where precipitation also decreases. In most tropical zones, maize yields are negatively affected, reflecting faster phenological development (White *et al* 2011) and lower precipitation during the growing period. Rising yields can be observed in some parts of AFR and LAM. The strongest average regional decreases occur in SAS (−9%) and in PAS (−7%) (SI appendix, table S3(a)). Under elevated atmospheric CO_2 concentrations, negative effects on maize yields occur in few aggregated regions, namely PAS and SAS (SI appendix, figure S7(a) and table S3(a)).

Grass yields decrease by 2% at the global area-weighted average for simulations assuming constant CO_2 levels. The strongest negative effects are visible in PAO (mainly Australia) and in MEA (−11% and −28% respectively), while grass yields rise in FSU and CPA. Figure 1(b) shows strong negative sub-regional effects (e.g. Sahel) as well as strong positive ones (e.g. East Africa) in all ten world regions, mainly reflecting changes in precipitation patterns. Under elevated CO_2 levels, the productivity of grassland rises by 14% at the global scale, while the regional signals range from 1% in PAS to 42% in FSU. Sub-regional patterns emphasize the beneficial effect of CO_2 fertilization on grassland productivity in moisture-limited areas (SI appendix, figure S7(b)).

We assess the sensitivity of our simulations to other climate projections for the SRES A2 emission scenario (Nakicenovic and Swart 2000), derived by 5 different GCMs (SI appendix, tables S3(b)–S3(f)). Resulting differences in yield projections mainly reflect differences between GCMs regarding simulated precipitation patterns (SI appendix, figures S9–S13). For maize, there is relatively good agreement across the GCMs in most regions, except in NAM, EUR and parts of FSU. For grass, projected yield impacts coincide only in MEA, PAS, and parts of AFR. In all other regions, strong differences can be observed between the GCMs. With full CO_2 fertilization, the differences across GCMs are much less pronounced.

3.2. Changes in cropland, rangeland, and intact forest

In the baseline, global cropland increases by 165 million ha between 2005 and 2045 (figure 2(a)). Cropland expansion is even larger in the 'climate_impact' scenario (197 and 213 million ha under constant and elevated CO_2 levels respectively) and the 'shift_to_mixed' scenario (222 and 207 million ha), while being smaller in the 'shift_to_rangeland' scenario (127 and 122 million ha). For all scenarios based on the IAASTD climate projection (independent to assumptions regarding CO_2 fertilization), changes in cropland area agree in sign in all regions except in MEA, being positive for most regions and negative for CPA and SAS. Regional cropland mostly increases at the expense of rangeland. In contrast, both cropland and rangeland are expanded into forest in LAM and PAS (figure 2(c)), where vast areas of potentially productive land are currently under intact forest (see SI appendix for definition).

Results for the LPS transition scenarios reflect differences in feed conversion efficiencies and the relative shares of concentrates and roughage within feed baskets. In the 'shift_to_rangeland' scenario, changes in cropland areas are smaller than in the 'climate_impact' scenario in most regions (−70 and −91 million ha globally under constant and elevated CO_2 levels respectively), except in NAM, EUR, and PAO. In NAM, feed conversion efficiencies are higher in rangeland-based systems than in mixed systems (SI appendix, figures S5–S6) (Herrero *et al* 2013). Hence, rangeland can be converted into cropland and R&D investments can be reduced (SI appendix, figure S15). In contrast, additional 169 million ha (252 million ha with CO_2 effect) are converted from intact forests into rangeland in LAM, due to much lower feeding efficiencies in rangeland-based systems (figure 2(c)). In the 'shift_to_mixed' scenario, more cropland is used in most regions apart from e.g. PAS and SAS, while rangeland is reduced by 90 million ha (21 million ha under elevated CO_2 levels). Deforestation in LAM is strongly reduced, compared to both the baseline and 'climate_impact' scenario and irrespective of assumptions concerning CO_2 fertilization. Required technological change rates are lower in most regions and deforestation is abated by about 76 million ha globally (27 million ha with CO_2 effect).

Results are sensitive to the choice of climate projection and assumptions about CO_2 fertilization, where cropland simulations in AFR, FSU and LAM show a particularly wide range of uncertainty. Moreover, sign and magnitude of secondary climate impacts on rangeland and intact forest are strongly influenced by underlying climate projections and the effectiveness of CO_2 fertilization. Overall dynamics of the LPS transition scenarios (relative to the respective 'climate_impact' simulations) are in most cases unaffected by the uncertainty in climate change impacts on agriculture (figure 2), but the magnitude of effects depends on assumptions regarding CO_2 fertilization. Including the full CO_2 effect leads in most regions to a further decrease in rangeland and expansion of cropland, compared to the baseline. In LAM, however, expansion of both cropland and rangeland is reduced, also slowing down deforestation.

3.3. Changes in global and regional agricultural production costs

In the 'climate_impact' scenario, global agricultural production costs increase by about 3% relative to the baseline in 2045 due to negative climate impacts

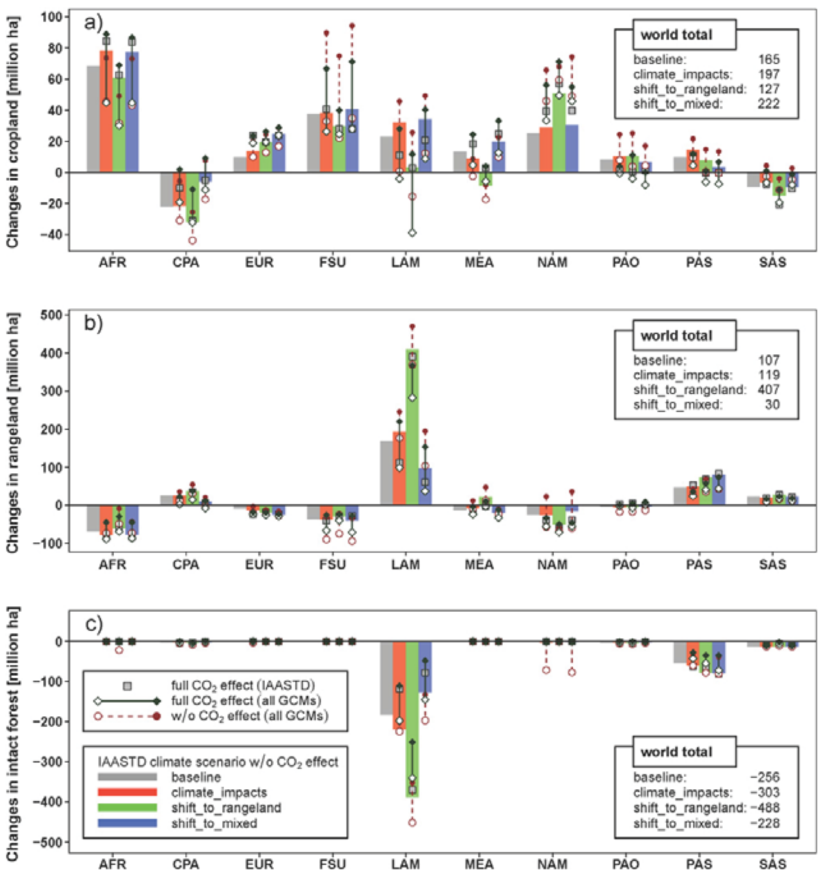

Figure 2. Changes in (a) cropland, (b) rangeland, and (c) intact forest by region (colored bars show differences between 2045 and 2005 in million ha for the IAASTD climate scenario; error bars show minimum and maximum change from sensitivity analysis with five additional climate model inputs (dark red dashed lines with circles indicating minimum (hollow) and maximum (solid) values for scenarios without CO_2 effect and dark green solid lines with diamonds for scenarios with full CO_2 effect); gray squares show results for the IAASTD climate scenario with full CO_2 effect).

(figure 3), which is equivalent to 145 billion US$. In MEA, agricultural production costs rise by about 16%, in SAS by 9%, in LAM by 5%, and in AFR by 2%. In CPA, by contrast, production costs drop due to climate impacts by about 3%. In the 'shift_to_rangeland' scenario, global agricultural production costs increase much more, by about 14%, while a transition towards mixed systems almost completely offsets detrimental climate impacts. In all regions except PAS, at least one of the considered shifts in LPS is not only suited to counterbalance the additional production costs caused by climate change, but also to reduce costs beyond the baseline level. In PAS however, where smallholder systems with relatively high feed conversion efficiencies dominate ruminant livestock production, both LPS transition scenarios covered here are detrimental compared to the reference setting.

Regional results are sensitive to uncertainties in climate projections. Even the sign of change in regional production costs may differ between different GCM inputs (figure 3). However, global production costs are less sensitive, as counteracting regional signals partly cancel each other out. Moreover, the observation that shifts in LPS offer the potential to alleviate climate change related costs in all regions (except PAS), is valid for all considered climate projections. We have also tested the sensitivity of agricultural production costs to CO_2 fertilization (figure 3, table S4) as well as to incomplete (i.e. 50%) LPS transitions, up to the year 2045 (table 3). The uncertainty in the effectiveness of CO_2 fertilization on agricultural yields heavily impacts on global and regional production costs. In most regions, the full CO_2 effect turns cost increases into cost decreases. Substantial cost increases in LAM and MEA in the 'shift_to_rangeland' scenario are considerably reduced. Incomplete transitions in LPS already have a relatively strong adaptive and cost reducing effect: a 50% shift to mixed systems lowers global adaptation costs from 3% of total agricultural production costs to 0.8%. Especially in more severely

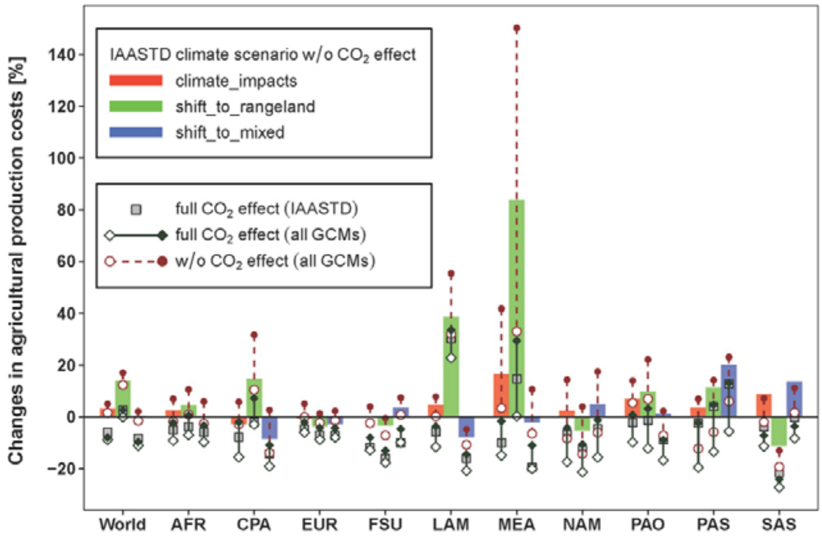

Figure 3. Changes in total agricultural production costs by region (colored bars show percent change to baseline in 2045 for the IAASTD climate scenario; error bars show minimum and maximum change from sensitivity analysis with five additional climate model inputs (dark red dashed lines with circles indicating minimum (hollow) and maximum (solid) values for scenarios without CO_2 effect and dark green solid lines with diamonds for scenarios with full CO_2 effect); gray squares show results for the IAASTD climate scenario with full CO_2 effect).

affected regions like MEA, SAS and LAM (16%, 9%, and 5% increase in production costs), incomplete transitions in LPS substantially buffer detrimental impacts of climate change on agriculture: resulting changes in production costs relative to the baseline amount to 3% in MEA, −3% in SAS and −1% in LAM.

Acknowledging the uncertainty related to the choice of crop growth model, we compare agricultural adaptation costs based on the LPJmL-MAgPIE modeling suite to MAgPIE simulations which use crop yield simulations from EPIC and pDSSAT under evolving climate conditions according to the SRES A2 socio-economic scenario (SI appendix, table S4). Similar to uncertainties related to climate projections, variations across different GGCMs are more distinct at the regional than at the global level (SI appendix, figure S16). Especially in FSU, LAM, NAM and PAO, differences related to crop growth models dominate overall uncertainty in results, but general responses with regard to LPS transitions are robust, i.e. declining production costs associated with a shift towards rangeland based livestock production in FSU and NAM as well as with a shift towards mixed systems in LAM (and also in PAO for all but one simulation based on pDSSAT). Similar patterns and magnitude of effects across different GCMs and GGCMs are simulated for CPA, EUR and SAS. In MEA, general patterns with respect to LPS scenarios are preserved, but the magnitude of climate change impacts is generally lower for EPIC and both pDSSAT scenarios compared to LPJmL simulations. In AFR, production costs respond differently to LPS transitions under EPIC and pDSSAT crop yield projections, suggesting that also rangeland based LPS could buffer detrimental impacts on crop production. Results based on the two models simulating crop yields both with and without CO_2 effect (LPJmL and pDSSAT) show a good concordance with regard to overall adaptation costs at the global level excluding CO_2 fertilization (3% and 5% respectively) as well to the beneficial effects of elevated CO_2 concentrations (−6% and −3%).

4. Discussion and conclusion

A growing body of literature is exploring climate impacts on livestock (Seo and Mendelsohn 2008, Thornton *et al* 2009, Nardone *et al* 2010, Thornton and Gerber 2010, Gaughan 2012, Ghahramani and Moore 2013, Godber and Wall 2014) and rangeland productivity (Hopkins and Del Prado 2007, Tubiello *et al* 2007b, Morgan *et al* 2008). However, global assessments of climate change impacts on agriculture and possible adaptation options still largely disregard the livestock sector (Leclère *et al* 2014, Nelson *et al* 2014a, 2014b), thus neglecting its pivotal and potentially adaptive role within the whole agricultural system—with the noticeable exception of Havlík *et al* (2015). We add to the literature an integrated, process-based analysis of biophysical climate impacts and livestock-specific adaptation options, and a first quantification of how transitions in LPS can reduce regional and global agricultural adaptation costs. Our study's

Table 3. Impact of full convergence of LPS (100) versus half convergence of LPS (50) on agricultural production costs for the IAASTD climate scenario (changes in agricultural production costs (%) in 2045 relative to the reference scenario in 2045; no CO_2 effect, see table 1 for regional acronyms).

Scenarios		World	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
Shift_to_rangeland	100	13.8	4.3	14.7	−3.7	−3.4	38.6	83.7	−5.3	9.6	11.2	−11.2
	50	7.7	2.3	3.4	−1.7	−3.5	25.0	41.9	−1.8	6.5	7.1	−2.6
Shift_to_mixed	100	0.3	0.2	−8.5	−2.7	3.4	−7.8	−2.2	4.8	1.1	20.0	13.5
	50	0.8	0.1	−7.4	−2.3	1.7	−1.2	2.7	3.7	4.6	12.1	11.3

entry point into the complex livestock-climate-nexus is the importance of strategic feed sourcing in the light of the changing availability of resources due to climate change.

Based on a comprehensive impact modeling chain, we trace implications of different climate projections through the agricultural systems, starting with impacts on crop yields and rangeland productivity. Simulations indicate significant negative impacts on crop yields in several regions, i.e. AFR, NAM and SAS. Strongest positive climate impacts on livestock feed production occur in CPA, where most crops as well as rangeland experience an increase in productivity. The LPJmL model is capable of reproducing national yields as reported by the FAO (Fader *et al* 2010) and simulated climate impacts on agricultural productivity are well within the range of other estimates (Müller *et al* 2011, Müller and Robertson 2014). For wheat, our results (−6.9% to −3.8%) compare well with the study by Nelson *et al* (2010) which projects changes in rainfed wheat yields from −10% to −4%. For maize, we estimate average global yield changes of −9.3% to +3.5%, while their results indicate a reduction from −12% to −2%.

A major uncertainty is the effectiveness of CO_2 fertilization, i.e. the stimulation of photosynthesis in C3 crops (e.g. wheat, rice, soy) and C3 grasses, and reduced water requirements of all crops and grasses. A strong positive effect of elevated CO_2 levels is simulated for rangeland productivity (+14% compared to −2.3% with constant CO_2 levels). In ecosystem-based experiments, grassland production increased on average by +17% due to the stimulatory effect of double ambient CO_2, with higher responses in moisture-limited and warm-season grassland systems (Campbell and Stafford Smith 2000). The size of the CO_2 fertilization effect on crop yields attainable in the field is still subject to debate (Long *et al* 2006, Tubiello *et al* 2007a, Ziska and Bunce 2007), owing to many complex and interrelated plant processes and depending on water and nutrient availability. Experiments across plant types, climatic zones, and production systems illustrate the large variability of plant physiological and growth responses to elevated CO_2 (Wang *et al* 2012).

Results derived within the Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP) highlight both the importance and uncertainty of CO_2 fertilization for simulating climate impacts on agriculture and the critical role of model parametrization to understand differences in simulated responses to elevated CO_2 (Rosenzweig *et al* 2013). Moreover, studies based on ensemble crop modeling demonstrated the large uncertainty stemming from different modeling approaches and the representation and parametrization of important bio-chemical processes (Asseng *et al* 2013, Rosenzweig *et al* 2013, Bassu *et al* 2014). Crop yield projections under evolving climate conditions simulated by LPJmL (one of the GGCMs included in ISI-MIP) lie well within the range of ensemble uncertainty. The CO_2 effect as implemented in LPJmL is relatively strong, but within a plausible physiological range.

But even results without CO_2 fertilization could be too optimistic: LPJmL currently does not account for various co-limitations (e.g. nutrient limitations, imperfect management, pests and diseases) and extreme events like prolonged droughts or heavy rainstorms. Even though aggregate climate impacts are relatively small by 2045, extreme events could have severe impacts even earlier (Diffenbaugh and Scherer 2011). Moreover, we do neither account for shifts in livestock disease distribution and severity due to climate change (Thornton and Gerber 2010, Perry *et al* 2013, Godber and Wall 2014) nor for direct impacts of rising temperatures and extreme weather events on animals, impairing production (meat, milk and egg yield and quality) and reproductive performance as well as animal health and welfare (Thornton *et al* 2009, Nardone *et al* 2010, Lara and Rostagno 2013).

To reveal the full adaptive potential being inherent in the heterogeneity of regional feeding efficiencies and feed basket compositions across systems, we apply LPS transition scenarios with full system convergence until 2045. In all regions except PAS (and also PAO for one simulation based on pDSSAT), at least one LPS scenario offers the potential to alleviate climate change related costs, independent of the choice of climate or crop model, and thus represents a cost-effective and low-risk adaptation option. Responses of production costs with regard to LPS transitions are generally robust across different GGCMs used in this study, except in AFR where simulations based on EPIC and pDSSAT indicate that also rangeland based livestock production could buffer detrimental climate impacts on agriculture.

In many regions (i.e. CPA, LAM, MEA and PAO), mixed livestock systems are more efficient than rangeland-based systems in converting feed to food, while providing a range of additional benefits (Herrero *et al* 2009). Globally, shifts in LPS towards mixed crop-livestock systems can reduce agricultural adaptation costs from 3% to 0.3% of total production costs and simultaneously reduce tropical deforestation by about 76 million ha. Moreover, an integration of livestock and crop production is likely to be more resilient to climate extremes due to greater system and income diversity. A transition from agro-pastoral to mixed systems is already occurring for various reasons. In regions with strong population growth, farm sizes tend to decrease, and, without sufficient fallow periods or appropriate crop rotations, soil fertility and eventually farm productivity decline over time. Here, the role of livestock for provision of manure, nutrient recycling and additional farm income is essential. Rising opportunity costs of labor also prompt systems to evolve towards higher value products and stronger integration of agricultural activities (Herrero *et al* 2014). A better integration of crop and livestock production is an important target for sustainable intensification and growth with few externalities and many co-benefits (Russelle *et al* 2007, Herrero *et al* 2009, 2010b).

Our results indicate that in some regions, grazing systems are well suited to buffer negative climate impacts, e.g. in EUR, FSU, NAM and especially in SAS. Here, further increases in production of concentrate feeds, especially with increasing levels of irrigation, will be challenging in view of declining groundwater tables and soil fertility as well as biodiversity losses (Herrero *et al* 2010a, 2009). Thus, a shift towards rangeland based systems is clearly favored in SAS, leading to a cost reduction of 11.2% compared with the baseline, while substantial cost increases of 13.5% go along with a transformation to mixed livestock systems. Projecting autonomous shifts in LPS in response to climate change impacts on feed crops and rangeland, Havlík *et al* (2015) also show that the relatively more optimistic impacts of climate change on grass yields compared with crop yields favor grazing systems in some regions, inter alia in SAS.

Globally, more than 1 billion ha of rangeland are biophysically suitable for cropping, especially in AFR, FSU and NAM (Erb *et al* 2007, van Velthuizen *et al* 2007). In our scenarios, between 61 and 78 million ha of rangeland in AFR are converted into cropland by 2045. This is well below the potential of about 400 million ha, estimated by the World Bank (Morris *et al* 2009). Rangeland-based systems also entail various co-benefits. In areas where rain-fed cropping becomes economically infeasible due to rising temperatures or declining precipitation, rangeland-based production could be a more drought-resilient option for sustaining agricultural production and rural income (Jones and Thornton 2009). However, this requires appropriate livestock densities and timing over the year to avoid rangeland degradation. Well-managed rangelands may also support high levels of biodiversity and can sequester substantial quantities of carbon (Conant and Paustian 2002, Alkemade *et al* 2013, Soussana and Lemaire 2014).

Due to strong interdependencies between climate change adaptation and mitigation in agriculture and especially in the livestock sector, potential adaptation measures have to be assessed with regard to associated GHG emissions. The 'shift_to_rangeland' scenario in our analysis incurs, due to lower average feed-use efficiency, a strong increase in tropical deforestation with potentially high additional CO_2 emissions. This finding is consistent with results reported by Havlík *et al* (2014). In the 'shift_to_mixed' scenario, rangeland is converted into cropland, which would also potentially cause additional emissions, as rangelands contain higher levels of soil carbon (Lal 2002). Further research should deepen our understanding of co-benefits between mitigation and adaptation measures in the livestock sector.

In conclusion, we show that the global costs of climate change adaptation in agriculture amount to about 145 billion US$ in 2045 (about 3% of total production costs), which is an order of magnitude higher than the previously estimated annual agricultural productivity investments of 7.1–7.3 billion US$ required to increase calorie consumption enough to offset the detrimental impacts of climate change on the health and well-being of children (Nelson *et al* 2009). We also show that transitions in LPS can substantially reduce agricultural production costs and the demand for productivity increases in crop production, independent from the climate change scenario.

While public policy is often focussed on improving the climate resilience of crop production, our results emphasize that the livestock sector could significantly contribute to a climate-smart agriculture. As the uncertainty analysis in this paper illustrates, public support for agricultural R&D has to target a potentially wide range of future climate outcomes. In the face of these uncertainties, changes in the way livestock are reared represent an effective lever to improve agricultural resource management and economic outcome as well as a low risk adaptation measure with various co-benefits, possibly even contributing to emission reduction. If the right incentives are provided, a shift to mixed systems can reduce pressures on tropical forests from agriculture, increase market-orientated production, and improve rural livelihoods, especially in Africa and the Middle East, Latin America, and East Asia. Production standards, certification and taxation schemes targeting climate mitigation, together with agricultural R&D, planning regulations and infrastructure development aimed at climate-proofing agriculture, should be reconciled to allow livestock production to respond to both mitigation and adaptation imperatives.

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Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture

Supplementary information (SI Appendix)

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1. Extended model description

1.1. LPJmL (Lund-Potsdam-Jena dynamic global vegetation model with managed Land)
LPJmL is a process-based ecosystem model which simulates growth, production and phenology of 9 plant functional types (representing natural vegetation at the level of biomes (Sitch et al., 2003)) and of 11 crop functional types (CFTs, table S2) as well as managed grass (Bondeau et al., 2007). Carbon fluxes (gross primary production, auto- and heterotrophic respiration) and pools (in leaves, sapwood, heartwood, storage organs, roots, litter and soil) as well as water fluxes (interception, evaporation, transpiration, soil moisture, snowmelt, runoff, discharge) are modelled accounting explicitly for the dynamics of natural and agricultural vegetation. Carbon and water fluxes are directly linked to vegetation patterns and dynamics through the linkage of transpiration, photosynthesis and plant water stress. The photosynthetic processes are modelled according to Farquhar et al. (1980) and Collatz et al. (1992). Simulated crops and grasses explicitly account for the photosynthesis pathway (C3 vs. C4). The phenology and management dates (sowing and harvest) of different crop types are simulated dynamically based on crop-specific parameters and past climate experience, allowing for adaptation of varieties and growing periods to climate change (Bondeau et al., 2007; Waha et al., 2012). All processes are modelled at a daily resolution and on a global 0.5°x0.5° grid. At sowing, photosynthesis in LPJmL starts on the basis of leaf area index supplied from seed reserves. The daily assimilation by photosynthesis is allocated to four carbon pools: leaves, roots, harvestable storage organs (e.g. grains for cereals), and a pool representing stems and mobile reserves. At harvest, the biomass fraction of the storage organs

is considered the harvested yield. The suitability of the model (and its predecessor LPJ that did not include cropland) for vegetation/crop and water studies has been demonstrated before by validating simulated phenology and yields (Bondeau et al., 2007; Fader et al., 2010), river discharge (Biemans et al., 2009; Gerten et al., 2004), soil moisture (Wagner et al., 2003), evapotranspiration (Gerten et al., 2004; Sitch et al., 2003), irrigation water requirements and agricultural green and blue water consumption (Rost et al., 2008), as well as terrestrial carbon dynamics including permafrost soils and impacts of a changing climate (Schaphoff et al., 2013, 2006).

Simulated crops and grasses explicitly account for the photosynthesis pathway (C3 vs. C4). Under elevated atmospheric CO2 concentrations, net photosynthesis is stimulated in C3 plants by increasing the CO_2 concentration gradient between air and the leaf interior. C4 plants (i.e. maize and millet) do not experience direct stimulation of their photosynthesis as wheat, rice, soy etc. (all C3). The canopy conductance is reduced in all plants under elevated atmospheric CO_2 concentrations and thus leads to reduced water requirements and beneficial effects in water-limited regions. The LPJmL model represents both C3 and C4 grasses, and allows for mixed composition. However, grass establishment distinguishes between C3 and C4 by a simple temperature threshold. Up to annual mean temperatures of 15.5°C, C3 grasses establish, at or above 15.5°C C4 grasses establish, which also allows for combinations of the 2 grass types, but most areas are single grass-type stands.

For the simulations in this study, we did not allow for internal adaptation of sowing dates (Waha et al., 2012) nor for internal adaptation of variety selection as these processes represent already an adaption measure to climate change that interferes with the economic considerations of the land use model MAgPIE (see below). This approach of using biophysical data simulated with static management as input for the cost optimization, helps to avoid overlapping assumptions between the biophysical and economic model (Müller and Robertson, 2014). Especially in the case of aggregated measures to increase crop yields as implemented in MAgPIE (i.e. investments into research and development that includes i.e. breeding new varieties and better soil management (Dietrich et al., 2014)), an exclusion of yield enhancing management options within biophysical simulations guarantees consistency with the economic decision process.

The uncertainty in projected changes in precipitation patterns is large and may strongly affect regional crop yield responses to climate change (IPCC, 2007). Especially rain-fed crops' responses to climate change are strongly dependent on the choice of the general circulation model (GCM) used to translate greenhouse gas (GHG) emission pathways into climate patterns. The underlying climate pattern of our central climate scenario was provided by the IMAGE group for the IAASTD scenario in 5-year intervals (van Vuuren et al., 2007). We interpolated these data linearly to annual values and superimposed a detrended year-to-year variability extracted from the CRU data for 1971-2000 (New et al., 2000). To avoid repetitions of multi-annual climate signals (like, e.g. the 1970s showing a negative detrended anomaly), we re-ordered the detrended anomalies randomly before superimposing them on the linearly interpolated climate data from IMAGE. In comparison with other climate projections for the A2 SRES scenario (Nakicenovic et al., 2000) from CCSM3 (Collins et al., 2006), ECHAM5 (Jungclaus et al., 2006), ECHO-G (Min et al., 2005), GFDL (Delworth et al., 2006), and HadCM3 (Cox et al., 1999), the IAASTD scenario ranges in the middle (-5.5% globally) of the projected impact range: -3.3% (ECHAM) to -9.5% (GFDL).

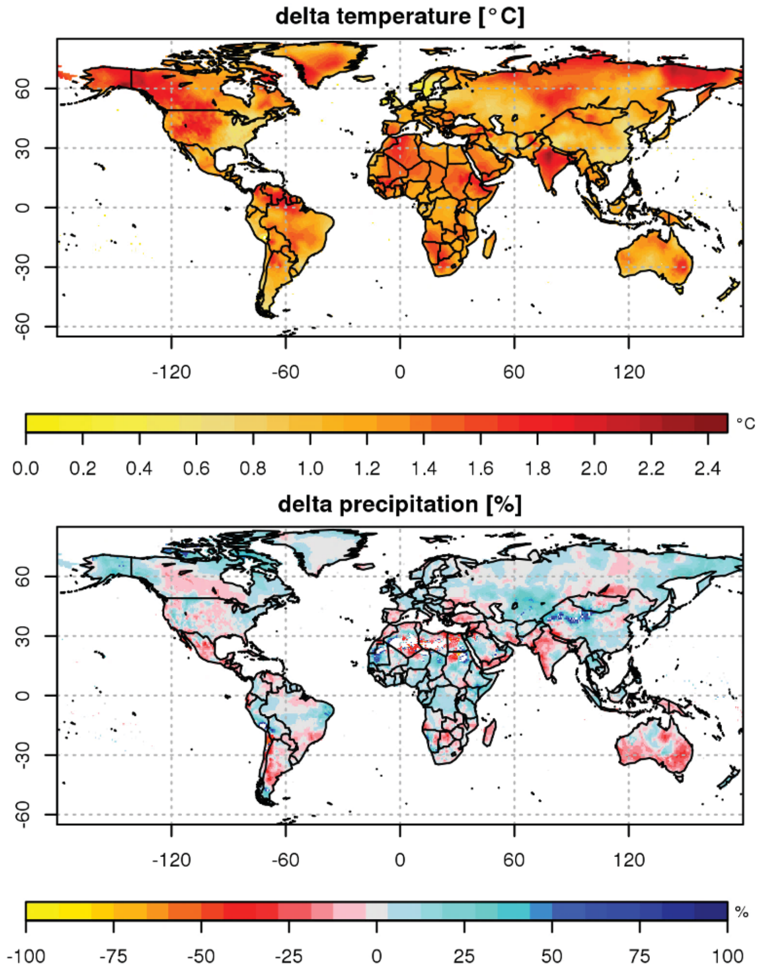

Figure S1. Changes in temperature (°C, upper panel) and precipitation (percent, lower panel) by 2045 (10-year average for 2040-2049), compared to 2005 (10-year average for 2000-2009) for the reference scenario of the International Assessment of Agricultural Science and Technology for Development (IAASTD) (McIntyre et al., 2009).

For each 10-year time step computed in the MAgPIE model, we supply 9-year average yields as simulated by LPJmL to avoid overly emphasis on year-to-year variability of crop yields. Management intensity in LPJmL is calibrated to match national yield levels as reported by FAOSTAT for the 1990s (Fader et al., 2010), but yield levels are recalibrated in MAgPIE to avoid inconsistencies in agricultural production due to mismatches in underlying land-use patterns.

1.2. MAgPIE (Model of Agricultural Production and its Impact on the Environment)

The Model of Agricultural Production and its Impact on the Environment (MAgPIE) (Bodirsky et al., 2014, 2014; Lotze-Campen et al., 2010, 2008; Popp et al., 2014, 2011) is a recursive dynamic optimization model with a cost minimization objective function, which has been coupled to the grid-based dynamic vegetation model LPJmL, with a spatial resolution of 0.5°x0.5°. It takes regional economic conditions such as demand for agricultural commodities, technological development and production costs as well as spatially explicit data on potential crop yields, land and water constraints (from LPJmL) into account. Each cell of the geographic grid is assigned to a socio-economic region (see figure S1). The objective function of the land- and water-use model is to minimize total costs of production for a given amount of regional food, feed and material (e.g. bioenergy) demand. For future projections, the model works on a time step of 10 years in a recursive dynamic mode. The simulation period starts in the calibration year 1995 which allows for a consistency check and benchmarking between projections and statistical data since 1995.

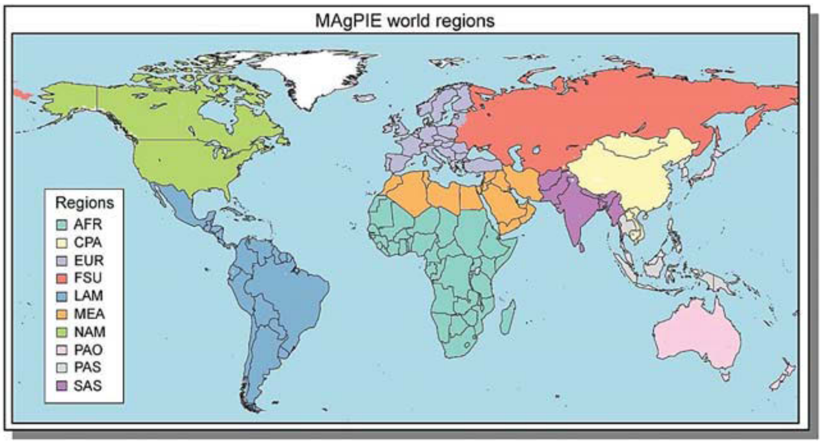

Figure S2. MAgPIE world regions (AFR: Sub-Saharan Africa; CPA: Centrally-planned Asia incl. China; EUR: Europe incl. Turkey; FSU: Former Soviet Union; LAM: Latin America; MEA: Middle East/North Africa; NAM: North America; PAO: Pacific OECD, i.e. Japan, Australia, New Zealand; PAS: Pacific Asia; SAS: South Asia incl. India).

MAgPIE is applied for a broad spectrum of research questions like climate change mitigation options, bioenergy, nutrient cycles, climate impacts, water scarcity, and trade. The LPJmL-MAgPIE modelling suite is part of a collective effort to systematically compare and integrate results from climate, crop, and economic models, within the frameworks of the Inter-Sectoral Impact Model Intercomparison Project (www.isi-mip.org) and the Agricultural Model Intercomparison and Improvement Project's global economic model intercomparison (www.agmip.org) (Lampe et al., 2014; Lotze-Campen et al., 2014; Nelson et al., 2014a, 2014b; Robinson et al., 2014; Schmitz et al., 2014; Valin et al., 2014). A comprehensive study exploring differences in land-use change trajectories up to 2050 across global agro-economic models including MAgPIE (four partial and six general equilibrium models) was carried out by Schmitz et al. (2014). Implementation and validation of important model features is presented in detail by Dietrich et al. (2014) for the endogenous implementation of yield-increasing technological change, Bodirsky et al. (2012) for the nitrogen cycle, Schmitz et al. (2012) for trade, and by e.g. Popp et al. (2014) for land use change dynamics and related CO_2 emissions.

The demand for food is regionally defined and given as an exogenous trend to the model, encompassing food crop categories and livestock product groups. For this study, future trends in population, food demand, dietary preferences (see table S1) and international trade are taken from a scenario run for the International Assessment of Agricultural Science and Technology for Development (IAASTD) (McIntyre et al., 2009). Livestock products are represented by six categories: beef, sheep and goat meat, pork, chicken, eggs, and milk. These commodities are produced in eight different livestock production systems (LPS) according to the updated International Livestock Research Institute/FAO classification (Herrero et al., 2013; Robinson et al., 2011): three rangeland-based systems (LG), and three mixed crop-livestock systems (MX), which are the aggregate of the mixed rainfed systems (MR) and mixed irrigated systems (MI) of the original FAO nomenclature, an industrial system, and a smallholder system. LG and MX systems are further differentiated by agroecological zones (arid and semiarid; humid and semihumid; tropical highlands and temperate). Pork, chicken, and eggs are only produced in industrial and smallholder systems, whereas ruminant meat and milk are mainly produced in rangeland-based and mixed systems. The parameterization of the different LPS, especially total feed efficiencies and the composition of feed baskets, relies on the dataset presented by Herrero et al. (2013) and is consistent with FAO statistics regarding livestock production, animal numbers, and livestock productivity. Feed for livestock consists of food crops, crop residues, processing by-products (e.g. brans, molasses and oil cakes) and green fodder harvested on cropland, and of biomass grazed on pastures. Regional feed demand is endogenously calculated depending on livestock production quantities, feed efficiencies and the composition of feed baskets.

Table S1. Scenario input data from the IMPACT model (McIntyre et al., 2009) (see figure S1 for regional acronyms).

	Population		Total calorie demand		Share of animal-based food in total diet	
	million		kcal/day/person		% of dry matter	
	2005	2045	2005	2045	2005	2045
World	6,438.3	8,851.8	2,632	3,447	8.2	9.2
AFR	747.7	1,563.2	2,036	2,393	3.0	4.1
CPA	1,430.2	1,581.9	2,827	4,504	11.6	17.4
EUR	611.6	622.1	3,391	3,931	14.1	13.8
FSU	263.6	234.4	2,826	3,472	10.1	8.7
LAM	550.9	763.1	2,680	3,617	11.3	11.5
MEA	343.3	580.9	2,565	3,409	5.0	5.9
NAM	330.5	429.5	3,604	4,389	15.6	13.9
PAO	152.3	147.1	2,865	3,293	13.2	15.7
PAS	475.9	607.5	2,520	3,513	5.0	7.2
SAS	1,532.3	2,322.1	2,205	3,078	3.4	5.3

The following cost types are integrated into the economic decision-making process of land allocation: Production costs per area are derived from the Global Trade Analysis Project (GTAP) Database (Narayanan and Walmsley, 2008) and contain variable inputs for labour, chemicals and other intermediate inputs. The model can endogenously decide to acquire yield-increasing technological change at additional costs (Dietrich et al., 2014). The costs for technological change for each economic region are based on its level of agricultural development, measured as agricultural land-use intensity (Dietrich et al., 2012). These costs grow with further investment in technological change, based on a cross-country regression analysis (Dietrich et al., 2014). The use of technological change is either triggered by its cost-effectiveness compared to other investments (e.g. land conversion costs) or as a response to resource constraints, such as land scarcity. Expansion of cropland is associated with land conversion costs, which are estimated on the basis of marginal access costs from the Global

Timber Model (Sohngen et al., 2009) and account for basic infrastructure investments and preparation of converted land (Krause et al., 2013; Popp et al., 2011).

Table S2. Regional Share of animal-based food in total diet on dry matter basis from the IMPACT model (McIntyre et al., 2009) (see figure S1 for regional acronyms).

	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
1995	3.0	9.3	14.5	11.0	11.3	4.8	16.4	12.7	4.2	3.2
2005	3.2	11.6	14.1	10.1	11.3	5.0	15.6	13.2	5.0	3.4
2015	3.4	13.5	14.0	9.6	11.6	5.3	15.2	13.8	5.8	3.7
2025	3.6	15.0	13.9	9.1	11.9	5.6	14.8	14.5	6.4	4.2
2035	3.8	16.3	13.8	8.9	11.8	5.8	14.3	15.1	6.9	4.7
2045	4.1	17.4	13.8	8.7	11.5	5.9	13.9	15.7	7.2	5.3

For the initial year 1995 of the simulation period, land use in MAgPIE is constrained by a spatially-explicit dataset of the following land pools: cropland, permanent pasture, forest (semi-natural forest including forestry and undisturbed natural forest), urban areas (which are static), and other land (snow, ice, other natural vegetation) (Krause et al., 2013). Cropland input is calculated according to the methodology described in Fader et al. (2010) from the MIRCA2000 dataset (Portmann et al., 2010). The permanent pasture pool is based on the spatially explicit information on grazing classes published by Erb et al. (2007). Forest inputs contain the forestry category as defined by Erb et al. (2007), and those parts of the unused category from the Erb et al. (2007) dataset that are covered by intact and frontier forests according to Potapov et al. (2008) and Bryant et al. (1997). Agricultural land use in MAgPIE is induced by 17 cropping activities (15 food crops, 1 fibre crop, and 1 forage crop) allocated to cropland and by livestock grazing on permanent pasture. Endogenous pasture dynamics driven by trajectories of feed demand are incorporated into the portfolio of land use change options. Not all land is suitable for cropping due to terrain- and agro-edaphic constraints. Therefore, we use the suitability index from Fischer et al. (2002) to restrict land that can be converted to cropland (Krause et al. 2013). Starting from this initial map, demand for cropland and pasture is induced by the biomass production required to fulfil the demand for food, feed and materials. Spatial distribution of crops and pasture within current agricultural land as well as the trade-off between land expansion and improvements of both crop yields and pasture productivity is based on the cost-effectiveness of the resulting land use pattern.

Attainable crop yields in MAgPIE are based on crop yield simulations computed with LPJmL for irrigated and non-irrigated conditions. In case of purely rain-fed production, no additional water is required, but yields are generally lower than under irrigation. In addition, LPJmL has been applied a priori to simulate cell specific available water discharge under potential natural vegetation and its downstream movement according to the river routing scheme implemented in LPJmL. If part of the grid cell is equipped for irrigation according to the global map of irrigated areas (Döll and Siebert, 2000), crops can be irrigated and additional water for agriculture is taken from available water discharge in the grid cell. Based on biophysical constraints, resource availability and socio-economic information, the model derives land- and water-use patterns and simulates major dynamics of the agricultural sector like land use change (including deforestation, abandonment of agricultural land and conversion between cropland and pastures), R&D investments and associated yield increases, interregional trade flows, and irrigation.

1.3. Regional composition of livestock production systems

The regional aggregation of harmonized livestock production systems (LPS), feed mixes and production statistics (calculated based on Herrero et al. (2013)) are shown in figures S2-S5. The major share of beef is produced in rangeland-based and mixed systems, with the exception of PAS, where most of the beef is produced in smallholder systems (figure S2). The shares for milk production are show in figure S3. The shares for sheep and goats are not shown here, since they are only important in selected regions.

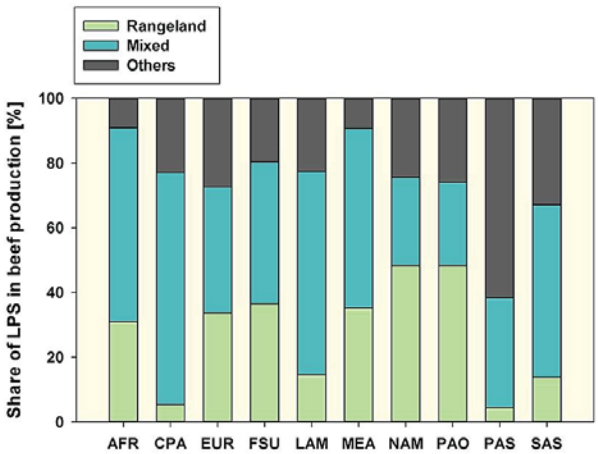

Figure S3. Share of different livestock production systems in total production of beef by region in 2000 (percent).

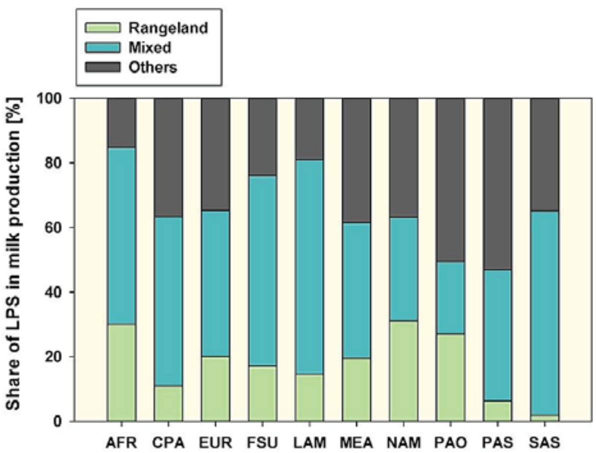

Figure S4. Share of different livestock production systems in total production of milk by region in 2000 (percent).

The average feed conversion efficiency for beef is higher in mixed systems than in rangeland-based systems in most world regions. However, in FSU, NAM, PAS, and SAS more feed is required per unit output in mixed systems compared to rangeland-based systems (figure S4). This is different for milk production (figure S5) where in some regions the different systems are very similar, while in most regions mixed systems are more efficient.

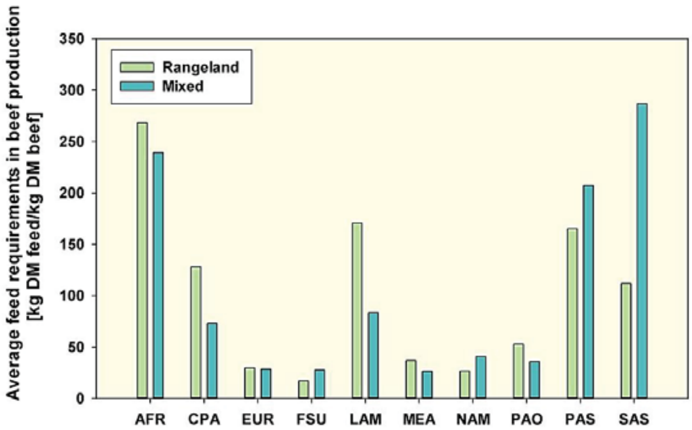

Figure S5. Average feed conversion efficiency for beef in different livestock production systems by region in 2000 (feed requirements in kg dry matter feed per kg dry matter beef).

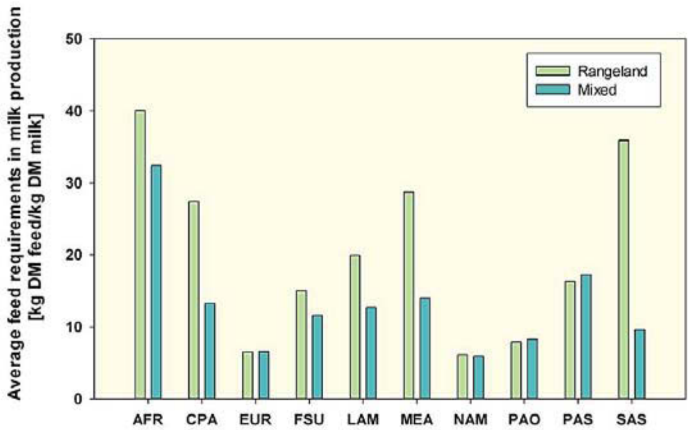

Figure S6. Average feed conversion efficiency for milk in different livestock production systems by region in 2000 (feed requirements in kg dry matter feed per kg dry matter milk).

2. MAgPIE mathematical description

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a nonlinear recursive dynamic optimization model that links regional economic information with grid-based biophysical constraints simulated by the dynamic vegetation model LPJmL. A simulation run with the simulation period T can be described as a set

$$X = \{x_t | t \in T\} \subseteq \Omega$$

of solutions of a time depending minimization problem, i.e. for every time step $t \in T$, the following constraint is fulfilled

$$\forall y \in \Omega: g_t(x_t) \leq g_t(y),$$

where the goal function for $t \in T$

$$g_t(x_t) = g(x_t, x_{t-1}, \dots, x_1, P_t)$$

depends on the solutions of the previous time steps $x_{t-1}, \dots, x_1$ and a set of time depending parameters P_t. We may interpret a MAgPIE simulation run $X = \{x_t | t \in T\} \subseteq \Omega$ as an element of the vector space $\Omega_t = \Omega \times T$.

Sets

The dimension of the domain Ω, on which for each time step the minimization problem is defined, and of Ω_t depends on the following sets:

- $T = \{\text{time steps } t\}$: Simulation time steps, where t denotes the current time step, $t - 1$ the previous time step and so on. The first simulated time step is $t = 1$.
- $I = \{\text{world regions } i\}$: 10 economic world regions.
- $J = \{\text{cells } j\}$: Highest spatial disaggregation level.
- $A = \{\text{land pools } a\}$: Following land pools are included: cropland ('crop'), permanent pasture ('past'), semi-natural forest (including forestry), intact and frontier forest, urban areas, other land (snow, ice, other natural vegetation).
- $SI = \{\text{suitability classes } si\}$: two classes are differentiated (suitable 'si0' and unsuitable 'non_si0' for cropping).
- $L = \{\text{livestock products } l\}$: Livestock production is represented by the following categories: beef, sheep and goat meat, pork, chicken, eggs, and milk.
- $V = \{\text{vegetal products } v\}$: Vegetal production is represented by the following categories: temperate cereals, maize, tropical cereals, rice, soybean, rapeseed, groundnut, sunflower, oil palm, pulses, potatoes, cassava, sugar cane, sugar beet, others (i.e. fruits and vegetables), cotton, fodder crops, pasture.
- $CR = \{\text{crops } cr\} = V \setminus \{\text{"pasture"}\}$: Vegetal products allocated to cropland.
- $K = \{\text{agricultural products } k\} = V \cup L$: Union of vegetal products V and livestock products L.

- $S =$ {livestock production systems s}: Livestock commodities are produced in three rangeland-based systems (LGA, LGH, LGT), three mixed crop-livestock systems (MXA, MXH, MXT), an industrial system, and a smallholder system.
- $H =$ {animal subcategories within herds h}: Dairy animals (BOVD, SGTD), replacers (BOVR, SGTR) and rest of the herd (BOVO, SGTO) for cattle and small ruminants respectively; laying hen (PTRH), broiler (PTRB), smallholder poultry (PTRX); pigs (PIGS, not further differentiated).
- $W =$ {water supply types w}: rainfed 'rf' and irrigated 'ir'.
- $C =$ {crop rotation groups c}: Groups of crops, which have similar requirements concerning crop rotation criteria.

To highlight the substance of our model equations with regard to the agricultural and economic content, we split our variable x_t into

$$x_t = \left(x_t^{area} \in \Omega^{area}, x_t^{land} \in \Omega^{land}, x_t^{prod} \in \Omega^{prod}, x_t^{anim} \in \Omega^{anim}, x_t^{tc} \in \Omega^{tc}\right) \in \Omega,$$

where the respective domains can be identified as the following vector spaces

$$\begin{array}{lcl} \Omega^{area} & = & \mathbb{R}^{|J|} \times \mathbb{R}^{|V|} \times \mathbb{R}^{|W|} \\ \Omega^{land} & = & \mathbb{R}^{|J|} \times \mathbb{R}^{|A|} \times \mathbb{R}^{|SI|} \\ \Omega^{prod} & = & \mathbb{R}^{|J|} \times \mathbb{R}^{|L|} \\ \Omega^{anim} & = & \mathbb{R}^{|J|} \times \mathbb{R}^{|S|} \times \mathbb{R}^{|H|} \\ \Omega^{tc} & = & \mathbb{R}^{|I|}. \end{array}$$

As a result, we may specify the dimension of the solution space for each time step as $\dim \Omega = |J| \cdot |V| \cdot |W| + |J| \cdot |A| \cdot |SI| + |J| \cdot |L| + |J| \cdot |S| \cdot |H| + |I|$ and the dimension of $\Omega_t = \Omega \times T$ as $\dim \Omega_T = |T| \cdot \dim \Omega = |T| \cdot (|J| \cdot |V| \cdot |W| + |J| \cdot |A| \cdot |SI| + |J| \cdot |L| + |J| \cdot |S| \cdot |H| + |I|)$. In the following, variables and parameters are provided with subscripts to indicate the dimension of the respective subdomains. Subscripts written in quotes are single elements of a set. The order of subscripts in the variable, parameter and function definitions does not change. The names of variables and parameters are written as superscript.

Variables

Since MAgPIE is a recursive dynamic optimization model, all variables refer to a certain time step $t \in T$. In each optimization step, only the variables belonging to the current time step are free variables. For all previous time steps, values were fixed in earlier optimization steps. As we have seen above, we distinguish five variables $x_t^{area} \in \Omega^{area}$, $x_t^{land} \in \Omega^{land}$, $x_t^{prod} \in \Omega^{prod}$, $x_t^{anim} \in \Omega^{anim}$ and $x_t^{tc} \in \Omega^{tc}$ that can be described as follows:

- $x_{t,j,v,w}^{area}$: Total area of vegetal production activity v and water supply type w, for each cell j and time step t [ha].
- $x_{t,j,a,si}^{land}$: Total area of unmanaged land pool a and suitability class si, for each cell j and time step t [ha].
- $x_{t,j,l}^{prod}$: Total production of livestock product l, for each cell j and time step t [ton dry matter].

- $x_{t,j,s,h}^{anim}$: Number of animals per livestock production system s and subcategory h, for each cell j and time step t [ton dry matter].
- $x_{t,i}^{tc}$: The amount of yield growth triggered by investments in R&D, for each region i and time step t [-].

Parameters

Besides variables, the model is fed with a set of parameters P_t. These parameters are computed exogenously and are in contrast to variables of previous time steps fully independent of any simulation output. Although most parameters are time independent, there exist also some parameters which are time dependent.

- $p_{t,j,v,w}^{yield}$: Yield potentials for each time step, cell, crop and water supply type taking only biophysical variations into account and excluding changes due to technological change. Values for this parameter are supplied by LPJmL and evolve over time under changing climate conditions [ton/ha].
- $p_{t,i,k}^{dem}$: Regional food, material and bioenergy demand for each time step and product [10^6 ton].
- $p_{t,i,s,h,k}^{fbask}$: Regional feed baskets prescribing the amount of feedstuff required to feed animals in livestock production system s and animal subcategory h [ton/ton].
- $p_{i,s,h,l}^{yield\_liv}$: Livestock production per animal [ton/LU].
- $p_{i,s,h,l}^{lps\_shr}$: Share of animals in different livestock production systems and subcategories for each region and livestock product [-].
- $p_{i,v}^{frv}$: Area related factor requirements for each crop and region based on the technological development level [US$/ha].
- $p_{i,l}^{frl}$: Production related factor requirements for livestock products for each livestock type and region [US$/ton].
- $p_{j,v}^{tranc}$: Spatial explicit transportation costs for vegetal products [US$/ton].
- $p_{i,a}^{lcc}$: Area related land conversion costs for each region and land type [US$/ha].
- p^{tcc}: Technological change cost factor accounting for interest rate, expected lifetime and general costs [US$/ha].
- $p_{i,v}^{\tau 1}$: τ-Factor representing agricultural land use intensity in the first simulation time step for each crop and region [-].
- p^{exp}: Correlation exponent between τ-Factor and technological change costs [-].
- $p_{i,k}^{sf}$: Regional self-sufficiencies for each product [-].
- $p_{t,i,k}^{exshr}$: Regional export shares for each product [-].
- p^{tb}: Trade balance reduction factor with $0 \leq p^{tb} \leq 1$ which is used to relax the trade balance constraints depending on the particular trade scenario [-].
- p_{j}^{aei}: Area equipped for irrigation in each cell [10^6 ha].
- $p_{t,j,v,w}^{watreq}$: Cellular water requirements for each product [m^3/ton/a].
- $p_{t,j,v,w}^{water}$: Amount of water available for irrigation in each cell [m^3/ton/a].
- p_{c}^{rmax}: Maximum share of crop groups in relation to total agricultural area [-].
- p_{c}^{rmin}: Minimum share of crop groups in relation to total agricultural area [-].

[all ton units are in dry matter]

Sub-functions

To simplify the general model structure, some model components which appear more than once in the model description and depend on the variables of the current time step t are arranged as functions:

$$
\begin{aligned}
f_{t,i}^{growth}(x_t) &= \prod_{r=1}^{t}\left(1 + x_{r,i}^{tc}\right) \\
f_{t,i,k}^{prod}(x_t) &= \sum_{j_i}\begin{cases} x_{t,j,k}^{prod} & : k \in L \\ \sum_{w} x_{t,j,k,w}^{area}\, p_{t,j,k,w}^{yield} f_{t,i}^{growth}(x_t) & : k \in V \end{cases} \\
f_{t,i,k}^{dem}(x_t) &= p_{t,i,k}^{dem} + \sum_{j_i,s,h} x_{t,j,s,h}^{anim} \cdot p_{t,i,s,h,k}^{fbask} \\
f_{t,k}^{xdem}(x_t) &= p^{tb} \cdot \sum_{i} f_{t,i,k}^{dem}(x_t)\left(1 - p_{i,k}^{sf} \cdot H\left(-p_{i,k}^{sf}\right)\right)
\end{aligned}
$$

- $f_{t,i}^{growth}$: Growth function describing the aggregated yield amplification due to technological change compared to the level in the starting year for each year t and region i.
- $f_{t,i,k}^{prod}$: Function representing the total regional production of a product k in region i for each time step t. In the case of vegetal products, it is derived by multiplying the current yield level with the total area used to produce this product. In the case of livestock products, it is represented by the related production variable.
- $f_{t,i,k}^{dem}$: Function defining the demand for product k in region i at time step t. It consists of an exogenous demand calculation for food and materials $p_{t,i,k}^{dem}$ and an endogenous demand for feed.
- $f_{t,k}^{xdem}(x_t)$: Function defining global excess demand for each product and time step which is not fulfilled within each world regions but via imports. H denotes the Heaviside step function.

Goal function

The objective or goal function $g_t(x_t) = g(x_t, x_{t-1}, \dots, x_1, P_t)$ defines the costs which are minimized in a recursive mode. The function depends on the solutions of the previous time steps. We define the goal function as follows:

$$
\begin{aligned}
g_t(x_t) = {} & \sum_{i,v}\left(p_{i,v}^{frv} f_{t,i}^{growth}(x_t) \sum_{j_i,w} x_{t,j,v,w}^{area}\right) + \sum_{i,l}\left(p_{i,l}^{frl} f_{t,i,l}^{prod}(x_t)\right) \\
& + \sum_{j,v,w} x_{t,j,v,w}^{area} p_{t,j,v,w}^{yield} f_{t,i(j)}^{growth}(x_t) p_{j,v}^{tranc} + \sum_{j,a}\left(p_{i(j),a}^{lcc} \sum_{si}\left(x_{t,j,a,si}^{land} - x_{t-1,j,a,si}^{land}\right)\right) \\
& + p^{tcc} \sum_{i}\left(x_{t,i}^{tc}\left(\frac{1}{|V|}\sum_{v} p_{i,v}^{\tau 1} f_{t,i}^{growth}(x_t)\right)^{p^{exp}} \sum_{j_i,v,w} x_{t-1,j,v,w}^{area}\right)
\end{aligned}
$$

The goal function describes total agricultural production costs which can be split in five terms: 1. area depending factor costs of vegetal production, which increase with the yield gain due to technological change; 2. factor costs of livestock production depending on the production level; 3. transportation costs for vegetal products from fields to markets ; 4. land conversion costs which arise, when non-agricultural land is cleared and prepared for agricultural production; 5. R&D investments to increase yields by improvements in management strategies and other inventions.

Constraints

Constraints describe the boundary conditions, under which the goal function is minimized.

Global demand constraints

$$\sum_i f_{t,i,k}^{prod}(x_t) \geq \sum_i f_{t,i,k}^{dem}(x_t)$$

These constraints are induced by global demand for agricultural commodities: Total production of a commodity k has to meet the global demand.

Trade balance constraints

$$f_{t,i,k}^{prod}(x_t) \geq p^{tb} \cdot \begin{cases} f_{t,i,k}^{dem}(x_t) + f_{t,k}^{xdem}(x_t) p_{t,i,k}^{exshr} & : \ p_{i,k}^{sf} \geq 1 \\ f_{t,i,k}^{dem}(x_t)\, p_{i,k}^{sf} & : \ p_{i,k}^{sf} < 1 \end{cases}$$

The trade balance constraints are similar to the global demand constraints, except that they act on a regional level. In case of exporting regions (self-sufficiency ratio for the product k is greater than 1), the production has to meet the domestic demand supplemented by the export volume. In case of importing regions (self-sufficiency ratio less than 1), the domestic demand is multiplied with the self-sufficiency ratio to define the amount that has to be produced by the region itself. In both cases, the demand is multiplied with the "trade balance reduction factor". This factor is always less than or equal to 1 and is used to relax the trade balance constraints depending on the trade scenario.

Livestock production system constraints

$$\sum_{j_i} x_{t,j,s,h}^{anim} \cdot p_{i,s,h,l}^{yield\_liv} \geq p_{i,s,h,l}^{lps\_shr} \sum_{j_i} x_{t,j,l}^{prod}$$

The livestock production constraints allocate animals to different livestock production systems, ensuring that a certain level of livestock commodities is produced.

Land constraints

$$\sum_{a} x^{land}_{t,j,a,si} = \sum_{a} x^{land}_{t-1,j,a,si}$$

$$\sum_{cr,w} x^{area}_{t,j,cr,w} = x^{land}_{t,j,"crop","si0"}$$

$$\sum_{si} x^{land}_{t,j,"past",si} = x^{area}_{t,j,"pasture","rf"}$$

$$\sum_{v} x^{area}_{t,j,v,"ir"} \leq p^{aei}_{j}$$

The land constraints guarantee that no more land is used for production than available. The first three sets of land constraints ensure the land availability for agricultural production in general. The last one secures that irrigated crop production is restricted to areas that are equipped for irrigation.

Water constraints

$$\sum_{v} x^{area}_{t,j,v,"ir"} p^{yield}_{t,j,v,"ir"} f^{growth}_{t,i(j)}(x_t) p^{watreq}_{j,v} + \sum_{l} x^{prod}_{t,j,l} p^{watreq}_{j,l} \leq p^{water}_{j}$$

Livestock as well as vegetal production under irrigated conditions depends on water. In each cell, water demand must be less or equal to the water available for agriculture.

Rotational constraints

$$\sum_{v_c} x^{area}_{t,j,v,w} \leq p^{rmax}_{c} \sum_{v} x^{area}_{t,j,v,w}$$
$$\sum_{v_c} x^{area}_{t,j,v,w} \geq p^{rmin}_{c} \sum_{v} x^{area}_{t,j,v,w}$$

Rotational constraints are used to prescribe typical crop rotations on cell level by defining for each vegetal production group a maximum and minimum share relative to total area under production.

3. Additional results

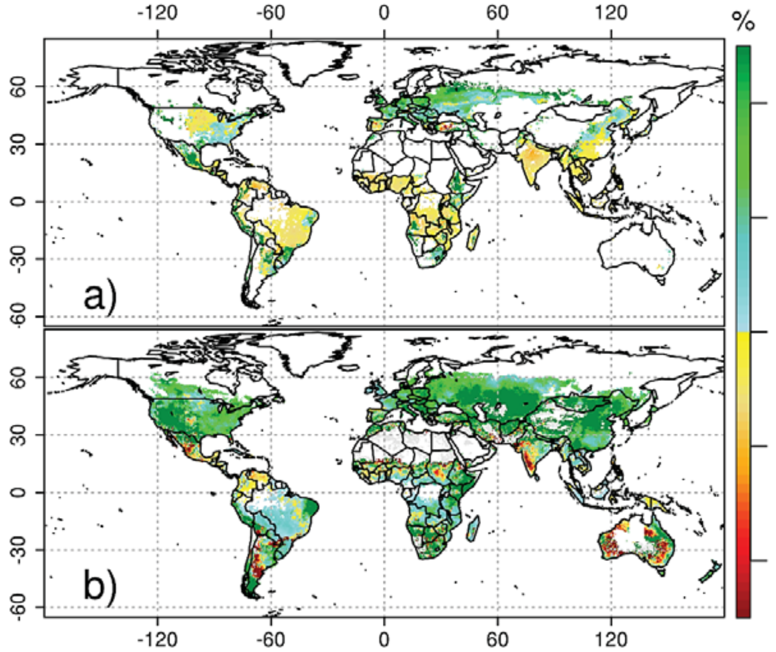

Figure S7. Climate impacts on maize yields (a) and rangeland productivity (b) by 2045 for the IAASTD climate scenario (percent change compared to 2005, LPJmL, full CO_2 effect, no nutrient limitations, adaptive harvest cycles).

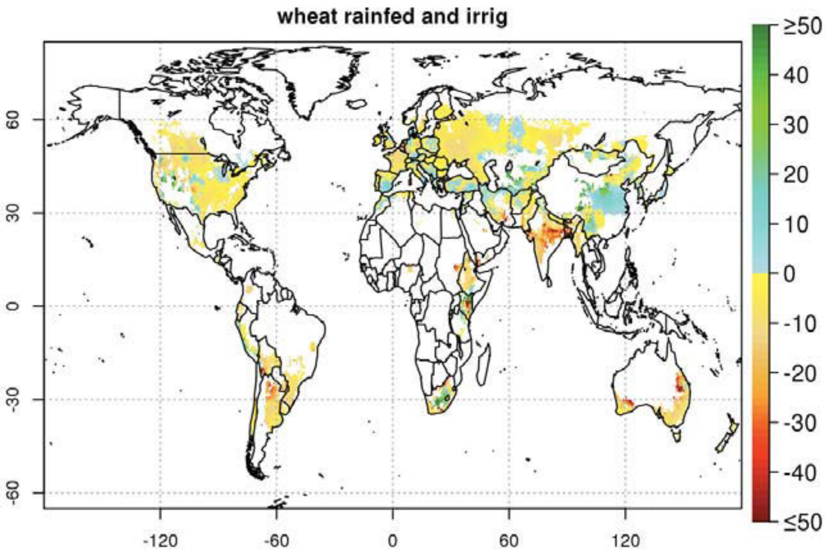

Figure S8. Climate impacts on wheat yields by 2045 for the IAASTD climate scenario (percent change compared to 2005, LPJmL, no CO_2 effect, no adaptation in cropping period or varieties, area-weighted mean of rain-fed and irrigated).

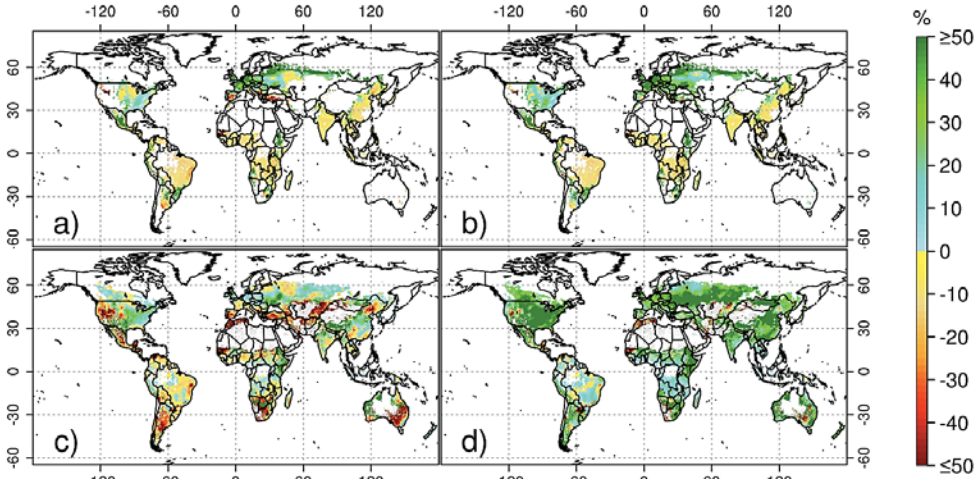

Figure S9. Climate impacts on maize yields, without CO_2 effect (a) and with full CO_2 effect (b), and rangeland productivity, without CO_2 effect (c) and with full CO_2 effect (d), by 2045 for the CCSM3 climate scenario (percent change compared to 2005, LPJmL, no nutrient limitations, adaptive harvest cycles).

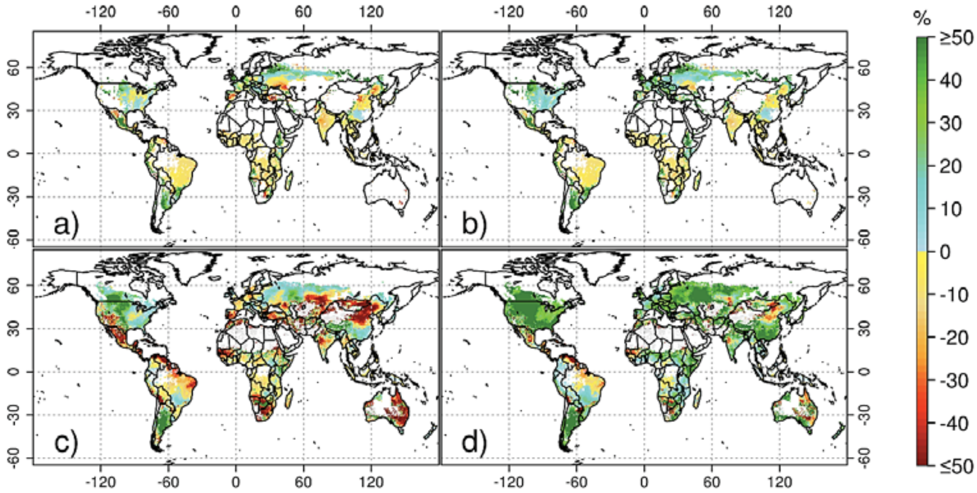

Figure S10. Climate impacts on maize yields, without CO_2 effect (a) and with full CO_2 effect (b), and rangeland productivity, without CO_2 effect (c) and with full CO_2 effect (d), by 2045 for the ECHAM5 climate scenario (percent change compared to 2005, LPJmL, no nutrient limitations, adaptive harvest cycles).

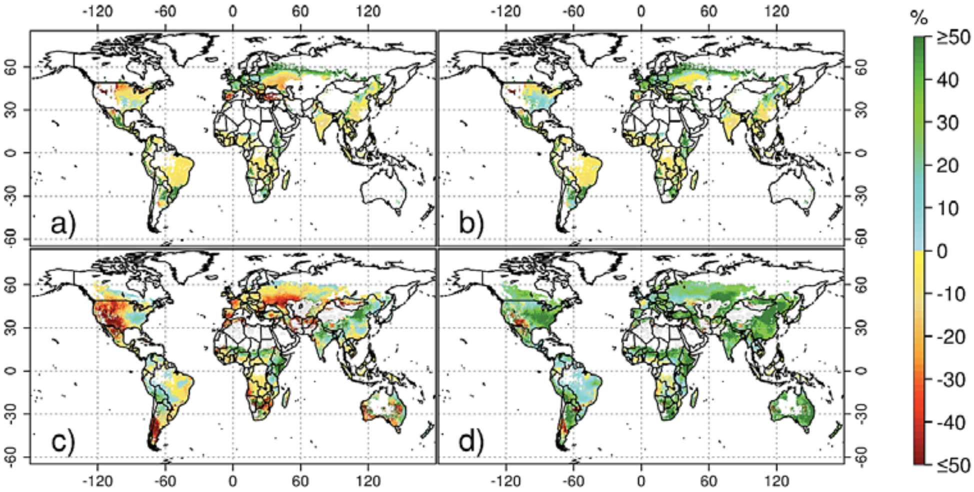

Figure S11. Climate impacts on maize yields, without CO_2 effect (a) and with full CO_2 effect (b), and rangeland productivity, without CO_2 effect (c) and with full CO_2 effect (d), by 2045 for the ECHO-G climate scenario (percent change compared to 2005, LPJmL, no nutrient limitations, adaptive harvest cycles).

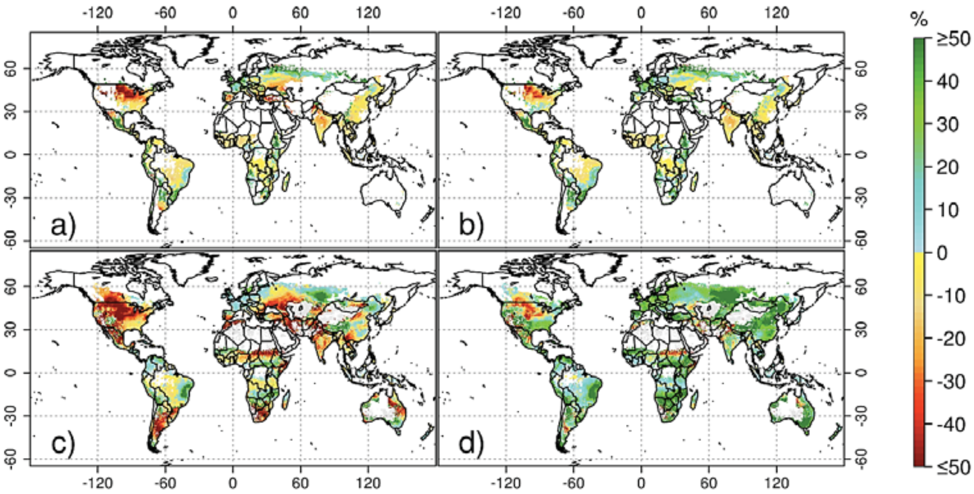

Figure S12. Climate impacts on maize yields, without CO_2 effect (a) and with full CO_2 effect (b), and rangeland productivity, without CO_2 effect (c) and with full CO_2 effect (d), by 2045 for the GFDL climate scenario (percent change compared to 2005, LPJmL, no nutrient limitations, adaptive harvest cycles).

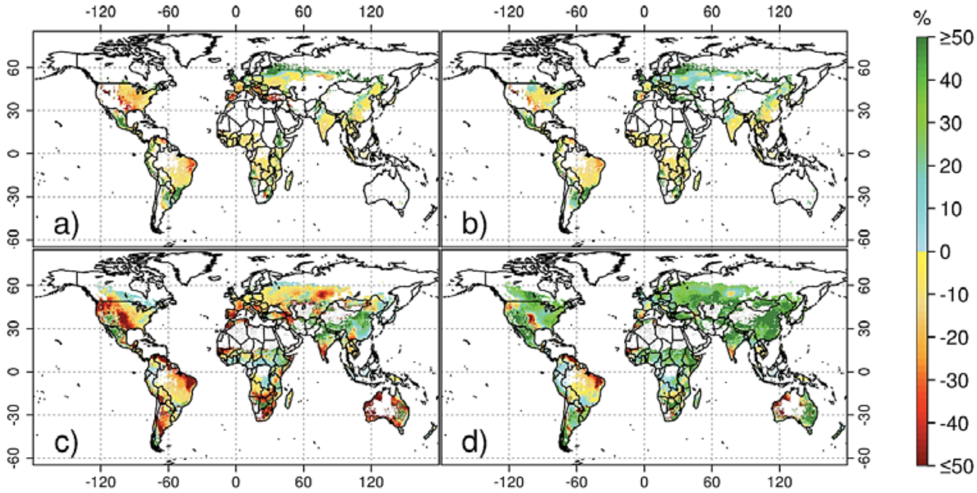

Figure S13. Climate impacts on maize yields, without CO_2 effect (a) and with full CO_2 effect (b), and rangeland productivity, without CO_2 effect (c) and with full CO_2 effect (d), by 2045 for the HadCM3 climate scenario (percent change compared to 2005, LPJmL, no nutrient limitations, adaptive harvest cycles).

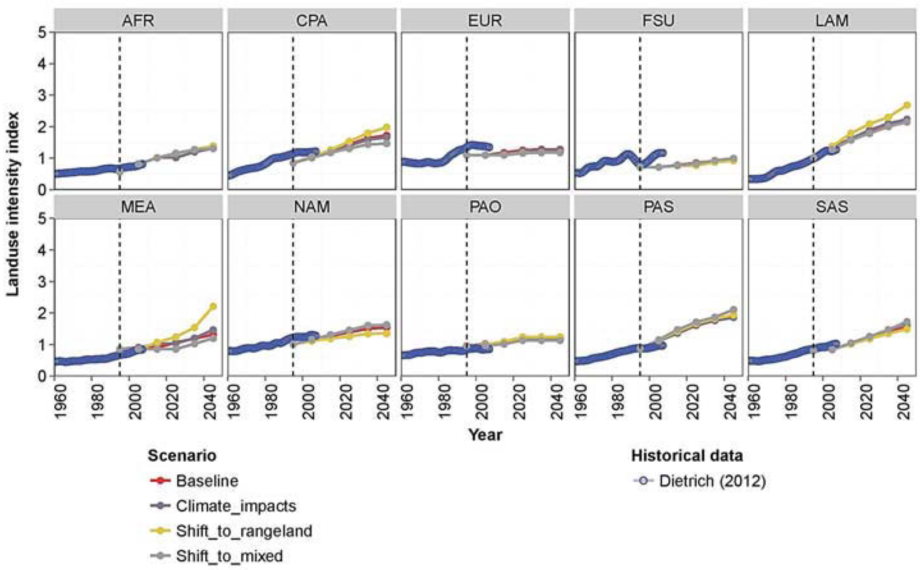

Figure S14. Landuse intensity index for the “Baseline” (red line), “Climate impacts”, “Shift_to_rangeland” and “Shift_to_mixed” scenarios until 2045. Increases over the simulation period reflect investments into yield increasing technological change (TC). Historical data from Dietrich et al. (2012). A vertical dashed line marks the start of the simulation period.

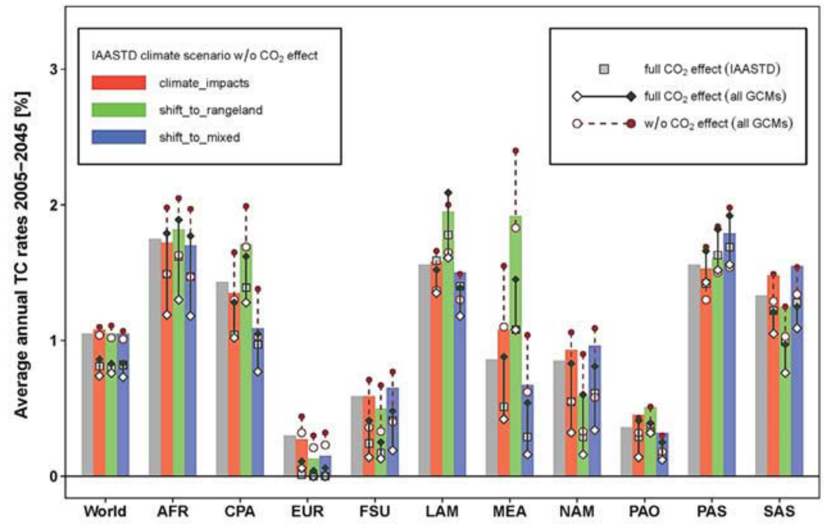

Figure S15. Required technological change (TC) rates by region (coloured bars show percent per year between 2005 and 2045; error bars show minimum and maximum TC rates from sensitivity analysis with five additional climate model inputs (dark red dashed lines with circles indicating minimum (hollow) and maximum (solid) values for scenarios without CO_2 effect and dark green solid lines with diamonds for scenarios with full CO_2 effect); grey squares show results for the IAASTD climate scenario with full CO_2 effect).

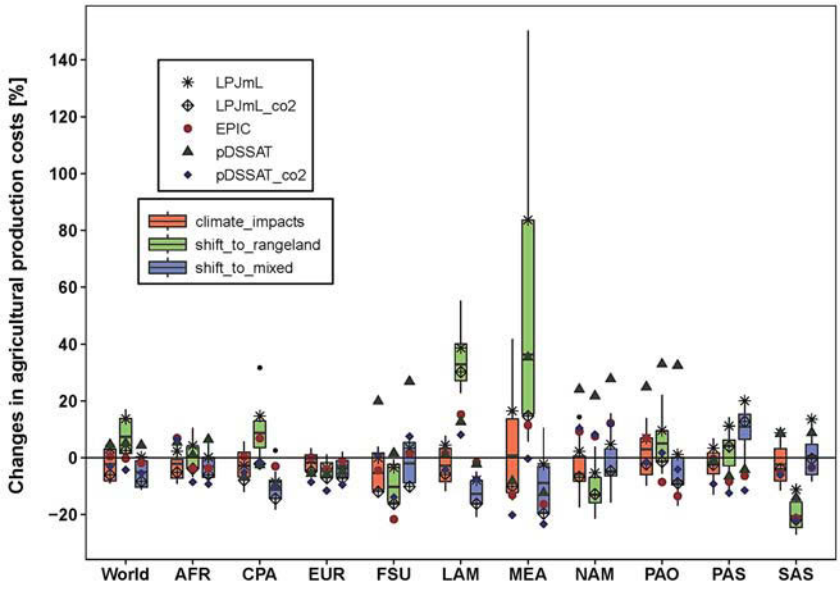

Figure S16. Changes in total agricultural production costs by region (coloured boxplots show percent change to baseline in 2045 across all GCMs both with and without CO_2 effect as simulated with the LPJmL-MAgPIE modelling suite; 2 different black shapes indicate values related to the LPJmL simulations for the IAASTD climate scenario; coloured shapes show values for different global gridded crop models simulated under HADGEM2-ES climate projections and SRES A2 socio-economic scenarios.

Table S3a. Climate impacts on crop yields per region for the IAASTD climate scenario by 2045, compared to 2005 (percent change, LPJmL, no adaptation in cropping period or varieties, area-weighted mean of rain-fed and irrigated) (see figure S1 for regional acronyms).

CO_2 constant	Wheat	Rice	Maize	Millet	Pea	Sugar-beet	Cassava	Sun-flower	Soy-beans	Ground-nut	Rape-seed	Others	Gras
World	-4.9	-10.8	0.2	-6.7	-13.5	-1.4	-6.8	-10.9	-6.0	-10.4	-5.8	-2.8	-2.3
AFR	-6.9	-13.8	3.2	-4.4	-6.1		-4.5	-10.6	-12.5	-10.5	-11.9	-1.3	-1.5
CPA	2.3	-4.6	-1.3	6.6	-4.0	5.6	-2.9	-5.1	1.5	-5.5	3.2	-0.3	5.2
EUR	-6.1	16.2	6.7	7.5	-14.2	-0.6		-14.8	1.2	3.9	-6.1	-1.8	-1.6
FSU	-3.7	7.6	-2.1	13.4	-6.7	-4.5	141.5	-13.4	7.4	9.4	-4.6	-3.6	2.9
LAM	-8.6	-8.8	5.9	-7.9	-10.5	-1.2	-8.4	-3.9	-10.5	-16.4	-10.9	-8.0	-4.1
MEA	-4.8	9.0	1.3	-4.3	-8.1	-5.3		-4.4	-4.3	1.9	-10.7	-10.3	-28.2
NAM	-2.3	-7.6	-2.1	-4.7	-7.1	-2.5		-6.5	-1.6	-6.9	-7.1	0.9	-2.0
PAO	-12.5	3.9	8.7	-22.2	-16.6	6.3		-34.6	-3.9	-6.2	-14.0	-12.7	-10.6
PAS	1.9	-12.0	-6.5	0.2	-4.0		-10.9	-23.0	-11.1	-10.4		-0.2	-3.0
SAS	-9.9	-17.9	-9.3	-12.7	-23.2	-2.8	-7.4	-18.4	-39.8	-17.8	-14.5	-6.3	-6.5
CO_2 dynamic													
World	5.5	10.3	4.8	-1.7	8.6	13.6	10.5	16.4	15.4	8.1	5.8	12.2	13.6
AFR	7.4	7.0	8.3	0.1	9.2		13.1	19.2	14.5	8.4	-3.3	9.6	11.7
CPA	11.8	11.6	0.7	12.3	13.8	23.0	14.0	27.6	18.4	11.9	11.5	21.9	32.8
EUR	3.2	30.3	14.4	23.1	9.6	13.8		13.9	20.8	24.3	5.4	21.0	20.5
FSU	6.6	22.0	5.8	24.8	9.0	13.0	156.2	12.2	27.0	49.9	5.5	25.1	42.1
LAM	2.7	9.1	9.9	-3.2	10.5	7.4	8.2	21.0	13.0	2.6	8.1	1.8	4.9
MEA	5.2	24.4	1.5	0.2	9.7	7.2		11.8	13.3	19.5	-4.0	14.2	13.3
NAM	8.5	7.0	2.9	3.0	10.0	13.0		19.6	16.3	11.6	5.2	27.8	32.5
PAO	0.7	17.2	9.8	-9.3	-0.7	17.1		16.8	14.0	17.0	-2.2	5.3	11.4
PAS	9.9	11.4	-6.0	0.7	7.6		6.1	30.7	12.4	6.8		1.8	1.4
SAS	3.1	7.9	-7.0	-8.5	6.5	18.7	12.7	13.3	19.6	1.9	1.3	4.7	20.2

Table S3b. Climate impacts on crop yields per region for the CCSM3 climate scenario by 2045, compared to 2005 (percent change, LPJmL, no adaptation in cropping period or varieties, area-weighted mean of rain-fed and irrigated) (see figure S1 for regional acronyms).

CO_2 constant	Wheat	Rice	Maize	Millet	Pea	Sugar-beet	Cassava	Sun-flower	Soy-beans	Ground-nut	Rape-seed	Others	Gras
World	-4.8	-10.4	3.1	-2.1	-8.3	1.8	-7.4	-4.7	-1.9	-9.2	-4.9	0.3	-2.2
AFR	-10.1	-13.2	0.2	-5.2	-7.1		-5.8	-10.6	-13.9	-13.6	-9.8	0.5	-3.1
CPA	1.2	-9.3	-6.4	6.6	-8.6	4.2	4.0	-14.5	-1.0	-9.0	2.6	-2.8	1.9
EUR	-6.5	8.8	5.4	24.0	-5.2	2.4		2.2	1.1	-3.7	-4.3	-1.9	0.2
FSU	-4.1	-3.3	6.3	22.9	-2.4	4.4	677.9	-1.4	9.8	15.6	-5.6	8.2	16.0
LAM	-6.0	-10.8	4.6	-7.5	-14.6	-5.3	-9.0	-13.4	-11.1	-16.8	-25.9	-11.8	-5.3
MEA	-3.0	-3.1	-4.9	-6.2	-8.1	-8.6		-3.9	-7.5	-3.3	-8.0	-10.1	-23.9
NAM	-1.6	-8.4	8.3	13.4	0.8	0.4		9.6	10.3	0.1	-9.3	16.3	17.8
PAO	-13.4	2.3	3.2	-7.3	-15.5	-1.1		-12.3	-1.4	-12.2	-16.1	-7.5	-6.6
PAS	-3.4	-13.0	-7.4	-4.1	-6.2		-11.3	-27.6	-13.6	-10.9		0.5	-0.5
SAS	-6.7	-10.8	-5.7	-2.9	-6.9	-5.6	-3.2	-9.5	-26.5	-5.3	-7.2	2.5	-1.0
CO_2 dynamic													
World	7.3	13.7	9.7	3.7	17.0	20.5	12.5	32.6	27.3	12.5	8.4	18.2	17.1
AFR	7.6	10.5	5.6	0.4	10.3		13.7	24.7	15.4	8.4	0.2	12.3	11.8
CPA	11.6	10.7	-3.8	13.9	12.2	25.1	26.0	25.8	20.0	11.4	11.8	26.7	38.3
EUR	4.3	25.0	15.3	48.2	24.2	20.1		48.2	30.1	20.1	9.8	25.0	28.1
FSU	7.3	14.0	16.2	39.4	18.3	26.8	751.7	34.2	35.2	50.1	5.3	46.1	65.0
LAM	7.6	10.1	9.7	-1.8	13.5	4.5	11.1	16.2	17.2	5.3	0.1	1.7	6.2
MEA	9.3	13.9	-4.8	-1.8	12.4	5.5		15.1	9.2	16.1	0.1	15.6	29.3
NAM	11.8	10.6	17.2	25.1	23.1	21.3		50.8	38.5	23.3	4.6	55.7	67.6
PAO	1.1	17.7	4.6	7.6	1.4	11.0		72.7	18.3	12.8	-2.8	16.8	24.5
PAS	5.9	12.7	-6.9	-2.9	7.2		8.4	36.0	15.2	9.1		2.6	4.6
SAS	8.2	17.6	-3.5	0.5	22.4	17.8	19.3	24.4	35.4	17.6	10.4	14.6	27.9

Table S3c. Climate impacts on crop yields per region for the ECHAM5 climate scenario by 2045, compared to 2005 (percent change, LPJmL, no adaptation in cropping period or varieties, area-weighted mean of rain-fed and irrigated) (see figure S1 for regional acronyms).

CO_2 constant	Wheat	Rice	Maize	Millet	Pea	Sugar-beet	Cassava	Sun-flower	Soy-beans	Ground-nut	Rape-seed	Others	Gras
World	-6.7	-8.7	3.5	-10.9	-15.6	-2.2	-10.2	-7.3	-7.2	-14.6	-7.8	-3.5	-9.7
AFR	-14.6	-19.1	-2.0	-15.4	-13.4		-8.3	-26.6	-25.9	-21.5	-13.6	-9.3	-13.5
CPA	-4.4	-1.4	-4.3	-4.1	-15.9	-5.8	-3.8	-27.3	-4.7	-8.7	-4.3	-11.1	-8.1
EUR	-10.8	18.3	4.2	26.9	-13.6	-3.6		-3.2	4.2	2.8	-15.9	-5.8	-2.9
FSU	-4.0	-0.2	1.5	14.4	-6.2	0.9	26.4	-3.7	7.0	-5.1	-2.4	0.4	-2.0
LAM	-8.4	-10.5	8.6	-11.0	-18.1	-8.8	-14.6	-8.3	-17.5	-10.0	-24.3	-11.6	-9.3
MEA	-1.9	7.1	0.7	-11.9	-7.2	-7.0		-4.3	-6.2	1.5	-8.0	-6.2	3.0
NAM	3.8	-6.0	7.9	19.1	3.2	4.1		12.0	6.3	-3.7	6.0	18.8	37.2
PAO	-15.1	0.0	-2.6	-42.9	-15.5	4.9		-53.5	-9.1	-29.8	-12.5	-16.4	-43.8
PAS	-3.9	-12.2	-5.4	2.3	-3.1		-11.1	-23.4	-13.7	-11.6		-1.2	-5.4
SAS	-10.3	-14.4	-11.5	-13.9	-22.6	-9.6	-10.1	-19.0	-57.5	-19.8	-12.9	-4.3	-7.1
CO_2 dynamic													
World	5.8	14.5	9.5	-4.1	9.7	15.9	9.7	24.4	18.3	6.7	6.4	14.5	8.1
AFR	2.6	3.7	3.5	-8.6	4.2		11.4	2.2	2.1	-0.6	-3.1	2.2	0.0
CPA	6.1	17.6	-0.3	5.1	6.1	16.0	17.3	7.8	17.0	12.5	6.0	15.1	24.0
EUR	1.3	34.8	13.4	48.7	13.6	14.3		31.1	27.8	26.2	-0.9	22.6	27.0
FSU	8.7	16.1	9.4	25.8	11.6	20.7	37.0	24.8	28.6	27.8	10.7	36.2	41.0
LAM	4.3	10.0	13.5	-5.3	8.6	0.5	4.8	20.0	10.8	11.6	-0.9	0.8	1.8
MEA	10.9	25.1	0.8	-9.5	12.2	6.8		13.8	11.6	21.3	-0.3	20.2	65.5
NAM	17.1	10.5	14.7	29.8	25.1	23.1		56.8	28.5	17.8	21.6	55.4	92.1
PAO	-1.1	15.0	-1.5	-31.9	2.5	17.5		-15.7	9.2	-10.6	0.7	3.2	-24.9
PAS	8.3	13.9	-4.1	4.8	11.8		9.0	41.9	15.6	8.8		2.0	0.7
SAS	4.3	12.6	-8.4	-8.8	8.5	12.5	12.2	14.8	-13.3	2.4	4.3	8.5	20.3

Table S3d. Climate impacts on crop yields per region for the ECHO-G climate scenario by 2045, compared to 2005 (percent change, LPJmL, no adaptation in cropping period or varieties, area-weighted mean of rain-fed and irrigated) (see figure S1 for regional acronyms).

CO_2 constant	Wheat	Rice	Maize	Millet	Pea	Sugar-beet	Cassava	Sun-flower	Soy-beans	Ground-nut	Rape-seed	Others	Gras
World	-5.7	-7.9	-5.3	-0.5	-9.1	-10.4	-6.5	-18.3	-12.6	-5.9	-7.3	-4.4	-4.3
AFR	-6.0	-9.4	2.4	-1.0	-3.4		-5.1	-6.7	-10.7	-5.8	-5.8	-2.2	-2.4
CPA	-2.7	-5.8	-5.2	3.3	-6.7	0.1	3.2	-16.5	-6.8	-7.7	-0.4	-5.5	-0.5
EUR	-7.9	23.5	-1.4	1.2	-17.1	-9.5		-19.3	-10.4	0.7	-11.0	-12.7	-14.7
FSU	-4.3	-3.6	-6.6	-3.2	-12.1	-13.1	385.0	-20.6	-3.1	31.8	-4.3	-9.1	-7.5
LAM	-6.7	-6.4	9.3	-7.3	-8.5	-8.0	-7.6	-14.8	-12.1	-8.3	-41.3	-4.2	-4.6
MEA	-2.6	1.0	-0.9	-3.0	-8.4	-6.9		-5.6	-9.1	1.2	-5.6	-6.5	-25.7
NAM	-6.9	-8.5	-12.5	-2.9	-21.1	-17.4		-31.5	-14.6	-3.9	-11.6	-7.5	-20.4
PAO	-5.5	-2.8	4.1	8.8	-8.7	-4.5		-0.1	2.1	-2.7	-5.8	3.1	9.1
PAS	-4.0	-9.6	-6.0	-0.6	-3.9		-10.1	-19.3	-9.7	-7.9		-1.7	-2.5
SAS	-3.9	-9.9	-3.2	1.5	-4.9	-4.4	-3.5	-4.1	-9.6	-3.3	-3.6	3.4	-0.2
CO_2 dynamic													
World	6.5	15.2	1.3	5.2	15.2	7.3	13.5	13.8	13.3	15.8	6.4	13.3	13.9
AFR	11.3	13.1	7.9	4.2	14.1		14.8	29.3	18.2	15.9	4.4	10.4	13.4
CPA	8.0	12.9	-2.5	11.4	15.8	19.8	25.1	26.9	13.8	13.5	8.9	22.4	33.5
EUR	2.5	41.5	8.7	21.1	6.2	7.6		13.4	13.0	25.0	2.8	13.2	10.9
FSU	8.2	13.3	2.8	12.5	6.9	8.4	433.3	9.6	18.9	70.0	7.6	25.1	34.8
LAM	6.3	13.0	13.7	-2.0	15.9	1.7	11.9	12.1	14.1	13.3	-21.5	8.3	5.8
MEA	9.9	18.4	-0.8	0.9	10.4	6.9		12.2	8.2	21.3	2.3	18.6	25.6
NAM	7.9	8.6	-4.0	7.5	-0.9	0.0		4.5	8.9	18.6	4.1	26.3	16.4
PAO	8.9	12.0	5.9	22.4	10.4	7.3		64.9	22.1	21.2	8.2	31.2	42.7
PAS	6.8	15.5	-5.2	0.9	9.6		10.0	46.9	19.8	11.7		0.6	3.1
SAS	11.1	17.8	-0.7	5.1	26.6	18.6	19.3	28.9	57.8	19.1	14.0	16.4	27.5

Table S3e. Climate impacts on crop yields per region for the GFDL climate scenario by 2045, compared to 2005 (percent change, LPJmL, no adaptation in cropping period or varieties, area-weighted mean of rain-fed and irrigated) (see figure S1 for regional acronyms).

CO_2 constant	Wheat	Rice	Maize	Millet	Pea	Sugar-beet	Cassava	Sun-flower	Soy-beans	Ground-nut	Rape-seed	Others	Gras
World	-3.8	-14.9	-9.3	-11.3	-13.0	-2.4	-8.8	-12.4	-22.1	-12.4	-4.7	-8.3	-6.3
AFR	-11.2	-20.7	-9.9	-13.7	-10.8		-4.2	-33.2	-22.5	-16.5	-11.4	-3.4	-3.2
CPA	1.6	-10.4	-4.0	4.1	-3.1	2.9	-1.0	-0.6	-4.3	-5.5	2.3	-5.0	3.5
EUR	-4.8	6.9	-2.2	11.5	-4.9	0.3		-6.7	-5.0	4.0	-3.2	0.7	1.2
FSU	-4.0	-0.8	-4.9	-10.5	-5.3	-4.4	7.6	-11.5	-1.5	-1.0	-4.5	-6.0	-7.2
LAM	-9.8	-12.3	7.3	-12.0	-17.1	-4.9	-8.4	-11.4	-26.2	-19.6	-21.0	-12.3	-9.5
MEA	-4.2	-1.3	-3.0	-1.8	-10.2	-2.6		1.6	-2.6	0.8	-3.6	-11.7	-53.7
NAM	-8.5	-7.5	-21.8	-10.6	-19.7	-16.7		-44.8	-23.3	-11.0	-16.1	-12.9	-17.4
PAO	1.8	-4.7	-0.7	-22.4	2.9	-4.3		-36.5	-9.2	-15.8	-2.1	-4.9	-10.0
PAS	1.9	-23.4	-14.6	-7.2	-11.4		-19.2	-39.0	-26.2	-26.3		-14.6	-19.9
SAS	-0.8	-16.0	-8.6	-11.2	-18.4	3.9	-7.6	-20.6	-41.5	-15.1	-3.3	-3.1	-5.4
CO_2 dynamic													
World	8.2	9.2	-1.6	-4.6	13.4	14.5	12.8	20.5	9.5	9.1	9.0	10.8	16.2
AFR	6.7	3.6	-4.3	-7.9	7.4		17.9	-3.1	7.1	4.3	-0.1	11.5	15.3
CPA	12.8	8.2	-1.3	10.8	19.6	21.7	20.9	39.8	14.9	15.0	12.7	24.5	41.5
EUR	4.7	21.8	5.5	27.6	22.1	16.6		26.8	16.2	26.7	9.1	26.4	26.3
FSU	7.5	16.0	4.0	2.9	12.0	15.2	14.8	18.1	19.6	37.7	6.9	25.0	30.2
LAM	4.1	9.1	14.5	-4.4	9.6	4.5	13.4	22.3	6.8	5.4	3.0	2.3	6.4
MEA	8.8	14.7	-2.8	0.9	10.0	11.3		19.9	14.7	20.6	4.8	13.4	-19.6
NAM	6.0	10.4	-9.6	2.9	4.7	0.9		-6.9	9.0	13.0	0.0	17.7	19.3
PAO	18.3	9.2	0.7	-7.6	26.4	7.1		17.4	9.7	8.7	12.2	19.2	17.2
PAS	12.5	1.2	-13.0	-6.5	2.4		0.7	12.9	-1.3	-7.3		-9.8	-12.4
SAS	15.0	14.9	-5.0	-5.7	15.0	29.1	16.3	14.8	22.2	7.9	15.8	13.0	24.3

Table S3f. Climate impacts on crop yields per region for the HadCM3 climate scenario by 2045, compared to 2005 (percent change, LPJmL, no adaptation in cropping period or varieties, area-weighted mean of rain-fed and irrigated) (see figure S1 for regional acronyms).

CO_2 constant	Wheat	Rice	Maize	Millet	Pea	Sugar-beet	Cassava	Sun-flower	Soy-beans	Ground-nut	Rape-seed	Others	Gras
World	-6.9	-9.9	-7.8	-6.7	-14.1	-10.1	-8.7	-18.3	-18.7	-9.2	-7.6	-5.5	-8.2
AFR	-10.4	-15.2	-2.3	-6.9	-8.1		-5.1	-20.1	-20.1	-14.8	-9.6	3.8	-1.6
CPA	-2.0	-6.1	-2.9	6.3	-8.0	-3.1	-0.8	-13.4	-4.8	0.6	-0.8	-5.9	0.8
EUR	-4.6	9.2	-11.4	-7.6	-19.1	-11.0		-28.5	-17.7	1.8	-7.8	-13.8	-17.2
FSU	-10.8	4.6	-4.4	19.2	-12.7	-10.0	731.3	-12.4	6.0	50.3	-11.5	-9.0	-7.8
LAM	-11.9	-13.6	13.1	-14.3	-20.7	-4.6	-16.5	-13.1	-20.8	-16.0	-27.2	-17.5	-12.0
MEA	-2.5	2.6	-2.6	-5.7	-7.4	-6.4		-5.0	-6.4	-5.3	-1.8	-9.7	-21.2
NAM	-6.6	-21.8	-17.1	-22.2	-18.4	-11.3		-29.1	-20.7	-22.0	-10.0	-9.3	-13.6
PAO	-7.7	-0.6	3.9	-13.0	-10.5	-4.4		-22.7	-4.0	-9.7	-10.0	-7.4	-18.7
PAS	-2.8	-11.7	-7.1	-3.1	-6.1		-10.3	-17.9	-11.3	-10.4		0.5	-0.8
SAS	-15.4	-12.3	-4.7	-3.6	-10.9	-4.0	-9.1	-15.6	-11.0	-12.6	-13.2	5.3	7.6
CO_2 dynamic													
World	5.0	14.2	-0.9	0.7	12.5	7.4	12.1	15.5	8.4	14.2	5.6	11.9	10.8
AFR	6.8	6.9	3.4	-1.0	9.7		15.5	14.6	9.6	6.9	0.7	17.0	15.7
CPA	8.1	13.4	0.0	13.9	14.1	17.8	21.3	27.4	16.5	22.9	7.9	23.3	36.4
EUR	6.3	26.5	-2.0	12.4	6.5	5.2		6.0	8.3	27.2	5.8	11.1	7.1
FSU	0.5	22.7	5.9	38.7	7.3	13.1	826.0	20.3	31.7	98.0	-0.6	25.4	37.3
LAM	0.7	8.0	19.8	-7.3	8.3	5.3	3.4	15.3	7.5	7.6	-6.0	-4.9	-1.2
MEA	9.7	19.9	-2.4	-1.1	12.3	7.9		14.0	12.0	13.7	6.1	16.3	34.0
NAM	6.6	-1.4	-8.6	-10.0	2.2	6.9		13.0	4.6	4.0	4.8	22.7	25.3
PAO	8.2	15.2	5.6	2.3	9.6	8.2		47.1	15.7	13.5	4.1	17.1	11.0
PAS	7.6	13.7	-5.6	-1.2	7.9		10.6	50.7	18.7	10.5		3.2	5.3
SAS	-1.9	17.0	-0.9	3.4	23.8	21.3	18.8	24.4	69.4	14.6	3.3	16.2	44.0

Table S4. Changes in total agricultural production costs by region (percent change to baseline in 2045 simulated with different global gridded crop models; EPIC without CO_2 effect; LPJmL and pDSSAT both with constant and elevated CO_2 levels; LPJmL simulations for the IAASTD climate scenario; EPIC and pDSSAT simulations under HADGEM2-ES climate projections.

Scenarios		World	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
Climate_impact	LPJmL	3.2	2.3	-2.8	-0.7	0.0	4.5	16.5	2.3	6.9	3.4	8.8
	LPJmL_co2	-5.9	-5.1	-7.8	-4.8	-11.9	-5.8	-10.1	-6.7	-2.3	-2.4	-4.0
	EPIC	0.5	6.9	0.4	0.1	-4.5	1.6	-13.1	9.3	6.9	-0.3	-5.6
	pDSSAT	4.6	5.4	-6.9	-5.5	19.9	1.0	-8.2	24.1	24.9	-0.8	8.6
	pDSSAT_co2	-3.0	6.4	-5.1	-8.5	0.7	-4.2	-20.1	10.4	-1.6	-9.2	-6.1
Shift_to_rangeland	LPJmL	13.8	4.3	14.7	-3.7	-3.4	38.6	83.7	-5.3	9.6	11.2	-11.2
	LPJmL_co2	2.6	-3.8	-2.1	-7.1	-16.2	30.2	14.7	-12.8	-1.4	3.9	-21.7
	EPIC	-0.2	-3.8	6.8	-4.0	-21.6	15.2	11.5	7.6	-8.5	-8.4	-21.2
	pDSSAT	5.2	1.0	-2.5	-5.8	1.6	12.6	35.3	21.8	32.9	-6.5	-14.1
	pDSSAT_co2	-4.3	-8.6	-1.4	-11.5	-13.9	8.1	-0.3	8.2	1.8	-12.4	-22.0
Shift_to_mixed	LPJmL	0.3	0.2	-8.5	-2.7	3.4	-7.8	-2.2	4.8	1.1	20.0	13.5
	LPJmL_co2	-8.3	-5.9	-14.4	-7.2	-10.2	-16.2	-19.6	-4.7	-9.0	12.7	-0.4
	EPIC	-1.8	-3.7	-3.0	-1.1	1.2	-1.5	-16.3	12.2	-13.5	-6.4	-3.5
	pDSSAT	4.4	6.4	-9.8	-4.8	26.8	-2.2	-12.3	27.7	32.5	-4.1	8.8
	pDSSAT_co2	-5.4	-9.3	-10.0	-9.5	7.5	-7.4	-23.3	11.9	-4.1	-11.4	-3.2

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Chapter III: N_2O emissions from the global agricultural nitrogen cycle – current state and future scenarios

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N_2O emissions from the global agricultural nitrogen cycle – current state and future scenarios

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Abstract. Reactive nitrogen (N_r) is not only an important nutrient for plant growth, thereby safeguarding human alimentation, but it also heavily disturbs natural systems. To mitigate air, land, aquatic, and atmospheric pollution caused by the excessive availability of N_r, it is crucial to understand the long-term development of the global agricultural N_r cycle.

For our analysis, we combine a material flow model with a land-use optimization model. In a first step we estimate the state of the N_r cycle in 1995. In a second step we create four scenarios for the 21st century in line with the SRES storylines.

Our results indicate that in 1995 only half of the N_r applied to croplands was incorporated into plant biomass. Moreover, less than 10 per cent of all N_r in cropland plant biomass and grazed pasture was consumed by humans. In our scenarios a strong surge of the N_r cycle occurs in the first half of the 21st century, even in the environmentally oriented scenarios. Nitrous oxide (N_2O) emissions rise from 3 Tg N_2O-N in 1995 to 7–9 in 2045 and 5–12 Tg in 2095. Reinforced N_r pollution mitigation efforts are therefore required.

1 Introduction

More than half of the reactive nitrogen (N_r) fixed every year is driven by human activity (Boyer et al., 2004). The main driver of the nitrogen cycle remains agricultural production, whose ongoing growth will require ever larger amounts of N_r to provide sufficient nutrients for plant and livestock production in the future.

The industrial fixation of the once scarce nutrient contributed to an unrivaled green revolution of production in the second half of the 20th century. Yet, only 35 to 65 % of the N_r applied to global croplands is taken up by plants (Smil, 1999). The remaining share may interfere with natural systems: The affluent availability of N_r leads to biodiversity losses and to the destruction of balanced ecosystems (Vitousek et al., 1997). In the form of nitrous oxide (N_2O), N_r contributes to global warming (Forster et al., 2007) and is the single most important ozone depleting substance (Ravishankara et al., 2009). Finally, it contributes to soil (Velthof et al., 2011), water (Grizzetti et al., 2011), and air pollution (Moldanova et al., 2011). Brink et al. (2011) estimate that the damage caused by nitrogen pollution adds up to 70–320 billion Euro in Europe alone, equivalent to 1–4 % of total income.

Therefore, much effort has been dedicated to improving our knowledge about the global agricultural N_r cycle. Smil (1999) pioneered the creation of the first comprehensive global N_r budget, and determined the key N_r flows in agriculture, most importantly fertilizer application, biological nitrogen fixation, manure application, crop residue management, leaching, and volatilisation. Sheldrick et al. (2002) extended the nutrient budgets to phosphorus and potash. Galloway et al. (2004) included natural terrestrial and aquatic systems in the N_r cycle. Liu et al. (2010a) broke up the global agricultural nutrient flows to a spatially explicit level. Bouwman et al. (2005, 2009, 2011) were the first, and so far the only, to have simulated the future development of the N_r cycle with detailed regional N_r flows.

However, the description of the current state of the N_r cycle was often incomprehensive. Belowground residues were so far not considered explicitly by other global studies, even though they withdraw large amounts of N_r from soils, and their decay on fields contributes to N_r losses and emissions. Similarly, not all past studies included fodder crops in their

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budgets, although they make up a considerable share of total cropland production. Furthermore, no bottom-up estimate for N_r release by the loss of soil organic matter exists so far. Regarding future projections, substitution effects between different N_r inputs are usually not considered.

In this paper, we create new estimates for the state of the agricultural N_r cycle in 1995 and four future scenarios until 2095 based on the SRES storylines. Our study presents a comprehensive description of the N_r cycle and covers N_r flows that have not been regarded by other studies so far. We create detailed cropland N_r budgets, but also track N_r flows upstream towards the processing sector, the livestock system and final consumption. This unmasks the low N_r efficiency in agricultural production. We use an independent parametrisation of the relevant N_r flows, concerning for example N_r in crop residues or biological N_r fixation. This allows for the identification of uncertainties in current estimates. For future projections we use a closed budget approach that allows for substitution between cropland N_r inputs (like fertilizer, manure or crop residues) and for an endogenous calculation of livestock N_r excretion. The budget approach is also used to estimate total nitrogen losses from fertilization and manure management (the sum of N_2, NO_x, NH_y and N_2O volatilisation as well as N_r leaching). As N_2O emissions play a crucial role in a global context, our model estimates them explicitly. For this purpose, our study uses the emission parameters of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006).

The paper is set up as follows: In the methods section, we first describe the Model of Agricultural Production and its Impact on the Environment (MAgPIE) that delivers the framework for our analysis. Then we give an overview on the implementation of crop residues, conversion byproducts and manure in the model. The description of all major N_r flows is followed by a summary of the scenario designs. In the results section, we present our simulation outputs for the state of the N_r cycle in 1995 and our projections for inorganic fertilizer consumption, N_2O emissions and other important N_r flows. In the discussion section, we compare our estimates to other studies and integrate the findings to a comprehensive cropland N_r budget for 1995, highlighting the largest uncertainties. We also compare our scenarios for the rise of the N_r cycle in the 21st century to estimates of other studies. As it is a key driver of the N_r cycle, we examine the livestock sector in more detail. Finally, the implications of our findings on the threat of N_r pollution are followed by our conclusions and an outlook on the opportunities for mitigation.

2 Materials and methods

2.1 General model description

MAgPIE (Lotze-Campen et al., 2008; Popp et al., 2010, 2012; Schmitz et al., 2012) is a model well suited to performing assessments of agriculture on a global scale and to simulating long-term scenarios. It is comprehensive concerning the spatial dimension and covers all major crop and livestock sectors. Moreover, it features the major dynamics of the agricultural sector, like trade, technological progress or land allocation according to the scarcity of suitable soil, water and financial resources. As it treats agricultural production not only as economic value but also as physical good, it can easily perform analysis of material flows.

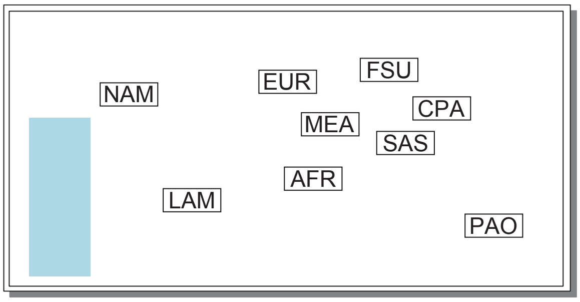

Fig. 1. The ten MAgPIE world regions. Sub-Sahara Africa (AFR), Centrally Planned Asia (CPA), Europe (including Turkey) (EUR), Former Soviet Union (FSU), Latin America (LAM), Middle East and North Africa (MEA), North America (NAM), Pacific OECD (Australia, Japan and New Zealand) (PAO), Pacific Asia (PAS), and South Asia (SAS).

MAgPIE optimizes global land-use patterns to settle a global food demand at minimal production costs. Food demand is exogenous to the model and differentiated into 18 crop groups and 5 livestock production types. The demand for feed depends on the livestock production quantity with individual feed baskets for each livestock category (Weindl et al., 2010). The demand for material consumption and the production waste are assumed to grow in proportion to food demand, while the production for seed is a fixed share of crop production. All demand categories are estimated separately for 10 world regions (Fig. 1) and have to be met by the world crop production. Additionally, the regions have to produce a certain share of their demand domestically to account for trade barriers (Schmitz et al., 2012). The production of crops requires financial resources as well as land and irrigation water. Production costs per area are derived from GTAP cost-of-firm data (Schmitz et al., 2010). Land requirements depend on the yield-level of the region, which are calibrated to meet 1995 FAO data. Higher production can either be reached by land expansion or by the purchase of yield-increasing technological change (Dietrich, 2011; Popp et al., 2011). Water availability and water requirements per crop are derived from the LPJmL model (Bondeau et al., 2007; Gerten et al., 2004). MAgPIE is solved for each 10-yr timestep between 1995 and 2095, whereby the cropland area and the level of technology are passed on from one timestep as input data to the consecutive timestep.

The existing model (as described in the Supplement) has been extended by a number of features in order to describe the dynamics of the N_r cycle. Crop residues and conversion byproducts from crop processing make up a major share of total biomass and were therefore integrated into the model (Sect. 2.2). Moreover, all dry matter flows were transformed into N_r flows. N_r flows in manure management, cropland fertilization and the transformation of N_r losses into emissions were included (Sect. 2.3). Finally, the scenario setup is described in Sect. 2.4. Detailed documentation as well as a mathematical description of all model-extensions can be found in Appendix A.

2.2 Crop residues and conversion byproducts

As official global statistics exist only for crop production and not for crop residue production, we obtain the biomass of residues by using crop-type specific plant growth functions based on crop production and area harvested. Plant biomass is divided into three components: the harvested organ as listed in FAO, the aboveground (AG) and the belowground (BG) residues. For AG residues of cereals, leguminous crops, potatoes and grasses, we use linear growth functions (Eggleston et al., 2006) with a positive intercept which accounts for the decreasing harvest index with increasing yield. For crops without a good matching to the categories of Eggleston et al. (2006), we use constant harvest indices (Wirsenius, 2000; Lal, 2005; Feller et al., 2007).

Based on Smil (1999), we assume that 15 % of AG crop residues in developed and 25 % in developing regions are burned in the field. Furthermore, developing regions use 10 % of the residues to settle their demand for building materials and household fuel. The demand for crop residues for feed is calculated based on crop residues in regional livestock specific feed baskets from Weindl et al. (2010). The remaining residues are assumed to be left on the field. We estimate BG residue production by multiplying total AG biomass (harvest + residue) with a crop-specific AG to BG ratio (Eggleston et al., 2006; Khalid et al., 2000; Mauney et al., 1994). All BG crop residues are assumed to be left on the field.

Conversion byproducts like brans, molasses or oil cakes occur during the processing of crops into refined food. We link the production of conversion byproducts to the domestic supply of the associated crops using a fixed regional conversion ratio. Feed demand for conversion byproducts is based on feed baskets from Weindl et al. (2010) and rises with livestock production in the region. All values are calibrated to meet the production and demand for conversion byproducts of FAO in 1995 (FAOSTAT, 2011). In case the future demand for feed residues or crop byproducts exceeds the production, they can be replaced by feedstock crops of the same nutritional value.

2.3 N_r flows

2.3.1 N_r content of plant biomass, conversion byproducts and food

The biomass flows of the MAgPIE model are transformed into N_r flows, using product-specific N_r contents. We compile the values for harvested crops, conversion byproducts, AG and BG residues from Wirsenius (2000); Fritsch (2007); FAO (2004); Roy et al. (2006); Eggleston et al. (2006) and Khalid et al. (2000). The N_r in vegetal food supply is estimated by subtracting the N_r in conversion byproducts from N_r in harvest dedicated for food. N_r in livestock food supply is calculated by multiplying the regional protein supply from each commodity group of FAOSTAT (2011) with protein to N_r ratios of Sosulski and Imafidon (1990) and Heidelbaugh et al. (1975). As food supply does not account for waste on the household-level, we use regional intake to supply shares from Wirsenius (2000).

2.3.2 Manure management

The quantity of N_r in livestock excreta is calculated endogenously from N_r in feed intake (consisting of feedstock crops, conversion byproducts, crop residues and pasture) and livestock productivity. The N_r in feed minus the amount of N_r in the slaughtered animals, milk and eggs equals the amount of N_r in manure. To estimate the mass of slaughtered animals, we multiply the FAO meat production with livestock-specific carcass to whole body weight ratios from Wirsenius (2000). N_r contents of slaughtered animals, milk and eggs are obtained from Poulsen and Kristensen (1998).

Manure from grazing animals on pasture is assumed to be returned to pasture soils except a fraction of manure being collected for household fuel in some developing regions (Eggleston et al., 2006). Manure from feedstock crops and conversion byproducts are assumed to be excreted in animal houses. We estimate that one quarter of the N_r in crop residues used as feed in developing regions stems from stubble grazing on croplands, while the rest is assigned to animal houses. Finally, we distribute all manure in animal houses between 9 different animal waste management systems according to regional and livestock-type specific shares in Eggleston et al. (2006).

2.3.3 Cropland N_r inputs

In our model, cropland N_r inputs include manure, crop residues left in the field, biological N_r fixation, soil organic matter loss, atmospheric deposition, seed and inorganic fertilizer.

For the manure managed in animal houses, recycling shares for each animal waste management system are adopted from Eggleston et al. (2006). The manure collected for recycling in developing regions is assigned fully to cropland soils, while it is split between cropland and pasture soils in developed regions. Additionally, all N_r excreted during stubble grazing is returned to cropland soils.

For crop residues left in the field, we assume that all N_r is recycled to the soils, while 80–90 % of the residues burned in the field are lost in combustion (Eggleston et al., 2006).

N_r fixation by free living bacteria in cropland soils and rice paddies is taken into account by assuming fixation rates of 5 kg per ha for non-legumes and 33 kg per ha for rice (Smil, 1999). The N_r fixed by leguminous crops and sugar cane is estimated by multiplying N_r in plant biomass (harvested organ, AG and BG residue) with regional plant-specific percentages of plant N_r derived from N_2 fixation (Herridge et al., 2008).

N_r release by the loss of soil organic matter after the conversion of pasture land or natural vegetation to cropland is estimated based on the methodology of Eggleston et al. (2006). Our estimates for 1995 use a dataset of soil carbon under natural vegetation from the LPJmL model (Sitch et al., 2003; Gerten et al., 2004; Bondeau et al., 2007). For 1995, we use historical land expansion from the HYDE-database (Klein Goldewijk et al., 2011a), while the land expansion in the future is estimated endogenously by MAgPIE.

The regional amount of atmospheric deposition on croplands for 1995 is taken from Dentener (2006). For future scenarios, we assume that the atmospheric deposition per cropland area grows with the same growth rate as the average regional agricultural NO_x and NH_y emissions.

The amount of harvest used for seed is obtained from FAOSTAT (2011). We multiply the seed with the N_r share of the harvested organ to estimate N_r in seed returned to the field.

Regional inorganic fertilizer consumption in 1995 is obtained from IFADATA (2011). For the scenarios, we use a closed budget approach. For this purpose, we define cropland soil N_r uptake efficiency (SNUpE) as the share of N_r inputs to soils (fertilizer, manure, residues, atmospheric deposition, soil organic matter loss and free-living N_r fixers) that is withdrawn from the soil by the plant. These withdrawals from the soil are calculated by subtracting N_r derived not from the soil (seed and internal biological fixation by legumes and sugarcane) from N_r in plant biomass. SNUpE is calculated on a regional level for the year 1995 and becomes an exogenous scenario parameter for future estimates. Its future development is determined by the scenario storyline (see Sect. 2.4).

In future scenarios, the soil withdrawals and the exogenous SNUpE determine the requirements for soil N_r inputs. If the amount of organic fertilizers is not sufficient, the model has to apply as much nitrogen fertilizer as it requires to balance out the budget. In our model, the N_r inputs to crops have no influence on the yield. We assume in reverse that a given crop yield can only be reached with sufficient N_r inputs. An eventual N_r limitation is already reflected in the height of the crop yield.

2.3.4 Emissions

Emission calculations are in line with the 2006 IPCC Guidelines of National Greenhouse Gas Emissions (Eggleston et al., 2006), accounting for NO_x, NH_y as well as direct and indirect N_2O emissions from managed soils, grazed soils and animal waste. Our estimates neither cover agricultural N_2O emissions from savannah fires, agricultural waste burning or cultivation of histosols, nor emissions from waste disposal, forestry or fertilizer production. Emission factors are connected directly to the corresponding N_r flows of inorganic fertilizer application, as well as residue burning and decay on field, manure management, manure application, direct excretion during grazing, and soil organic matter loss. We use a Monte Carlo analysis to estimate the effect of the uncertainty of the IPCC emission parameters on global N_2O emissions.

2.4 Future scenarios

For future projections, we analyse four scenarios based on the SRES storylines (Nakicenovic et al., 2000), varying in two dimensions: economy versus ecology and globalisation versus heterogeneous development of the world regions. The parametrisation of these scenarios differs in several aspects, which try to cover the largest uncertainties for the future development of the N_r cycle (Table 1). In the following, the scenario settings are shortly described, while a detailed description and an explanation of the model implementation is provided in Appendix A4.

Food demand projections and the share of calories from livestock products are calculated based on regressions between income and per-capita calorie demand (intake and household waste), as well as regressions between income and the share of livestock calories in total demand. The regressions are based on a panel dataset (5889 data points) from FAOSTAT (2011) and WORLDBANK (2011) for 162 countries from 1961 to 2007. In the environmentally oriented scenarios, we used different functional forms for the regressions that result in lower values for plant and livestock demand. The future projections are driven by population and GDP scenarios from the SRES marker scenarios (CIESIN, 2002a,b).

Trade in MAgPIE is oriented along historical trade patterns, fixing the share of products a region has imported or exported in the year 1995. To account for trade liberalisation, an increasing share of products can be traded according to comparative advantages in production costs instead of historical patterns. We use two different trade scenarios based on Schmitz et al. (2012), assuming faster trade liberalisation in the globalised scenarios.

The livestock production systems in the 10 MAgPIE regions differ in 1995 both regarding their productivity and the animal feed baskets. To account for the increasing industrialisation of livestock production, we assume an increasing convergence of the livestock systems from the current mix towards the industrialised European system. This highly

Table 1. Scenario definitions, based on the IPCC SRES scenarios.

	1995	2045				2095			
		A1	A2	B1	B2	A1	A2	B1	B2
GDP (10^{12} US$)	34	222	106	170	138	674	314	453	319
Population (10^9 heads)	5.7	8.6	10.8	8.6	9.2	7.4	14.8	7.4	10.4
Food demand (10^{18} J)	23	46	50	42	43	47	81	41	53
– Thereof livestock products	16 %	24 %	17 %	22 %	22 %	22 %	17 %	16 %	18 %
Trade patterns									
– Historical	100 %	60 %	88 %	60 %	88 %	37 %	78 %	37 %	78 %
– Comparative advantage	0 %	40 %	12 %	40 %	12 %	65 %	22 %	65 %	22 %
Livestock systems									
– Current mix	100 %	20 %	50 %	20 %	50 %	0 %	20 %	0 %	20 %
– Industrialised	0 %	80 %	50 %	80 %	50 %	100 %	80 %	100 %	80 %
Animal waste[1]									
– Current mix	100 %	30 %	80 %	40 %	80 %	0 %	50 %	20 %	50 %
– Daily spread	0 %	0 %	0 %	30 %	20 %	0 %	0 %	40 %	50 %
– Anaerobic digester	0 %	70 %	20 %	30 %	0 %	100 %	50 %	40 %	0 %
Soil N_r uptake efficiency (SNUpE)	51 %[2]	60 %	55 %	65 %	65 %	60 %	60 %	70 %	70 %
Intact and frontier forest protection		no	no	yes	yes	no	no	yes	yes

[1] Only for waste in animal houses.
[2] Global average.

productive system has a large proportion of feedstock crops and conversion byproducts in the feed baskets. In the globalised scenarios, convergence is assumed to be faster than in the regionalised scenarios.

Currently, regional animal waste management systems are diverse and their future development is highly uncertain. We assume two major future trends. Firstly, due to the scarcity of fossil fuels and the transformation of the energy system towards renewables, the use of animal manure as fuel for bioenergy will become increasingly important. Secondly, in the environmental scenarios, we also assume that an increasing share of manure is spread to soils in a timely manner. We therefore shift the current mix of animal waste management systems gradually towards anaerobic digesters and daily spread.

Improvements in the cropland soil N_r uptake efficiency may occur in the future due to increasing environmental awareness or to save input costs. The regional efficiencies have been calculated for 1995, and we assume that they gradually increase in all scenarios, with the environmental scenarios reaching the highest efficiencies.

Finally, the expansion of agricultural area into unprotected intact and frontier forests is restricted gradually until 2045 in the environmental oriented scenarios, as described in Schmitz (2012).

The scenarios start in the calibration year 1995 and continue until 2095. The base year 1995 facilitates the comparison with other studies (Smil, 1999; Sheldrick et al., 2002; Liu et al., 2010a) and allows for a consistency check and benchmarking between the scenarios and the real development since 1995.

3 Results

Detailed global and regional results of the current state of the agricultural N_r cycle and the four scenarios can be found in the Supplement. In the following, the most important results are summarised.

3.1 Global nitrogen cycle

3.1.1 State in 1995

According to our calculations for the year 1995, 205 Tg N_r are applied to or fixed on global cropland, of which 115 is taken up by cropland plant biomass. Thereof, 50 Tg are fed to animals in the form of feedstock crops, crop residues, or conversion byproducts, plus an additional 72 Tg from grazed pasture, to produce animal products which contain 8 Tg N_r. In total, plant and animal food at whole market level contains 24 Tg N_r, of which finally only 17 Tg N_r are consumed. Figure 2 shows an in-depth analysis of N_r flows in 1995 on a global level.

3.1.2 Scenarios

In our four scenarios, the throughput of the N_r cycle rises considerably within the 21st century. Total N_r in cropland plant biomass reaches 244 (B2)–323 (A1) Tg N_r in 2045 and 251 (B1)–434 (A2) Tg N_r in 2095. Also, the range of soil inputs increases throughout the century, starting with 185 Tg in 1995 to 286 (B2)–412 (A1) Tg N_r in 2045 and 286 (B1)–553 (A2) Tg N_r in 2095. Inorganic fertilizer consumption in the B scenarios show a modest increase to 121 (B2) and 145

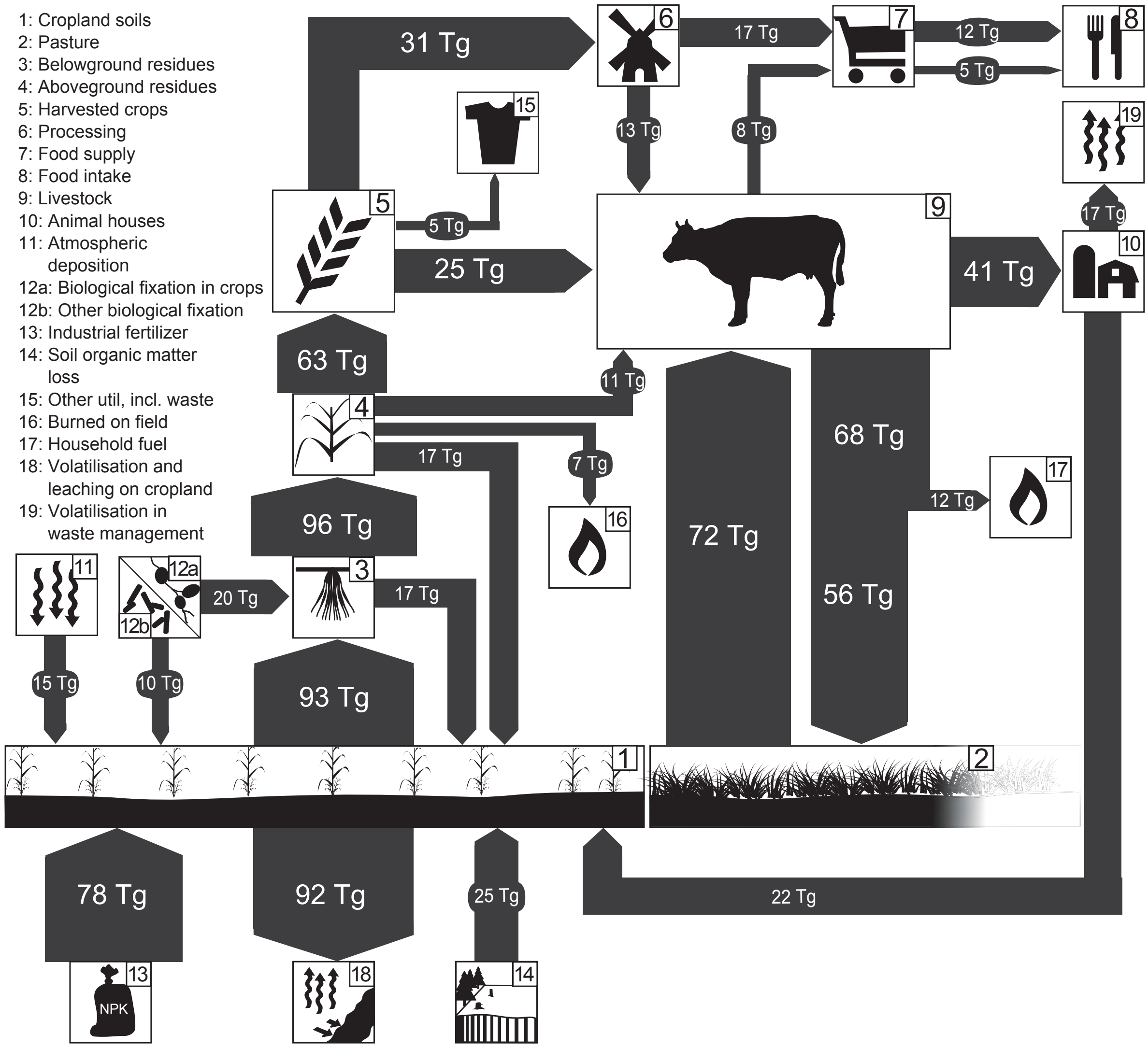

Fig. 2. Agricultural N_r cycle in Tg N_r in the year 1995. Flows below 5 Tg N_r are not depicted. No estimates were made for N_r inputs to pasture soils by atmospheric deposition and biological fixation.

(A1) Tg N_r until 2045 and a stagnating or even declining consumption thereafter, while the A scenarios exhibit a much stronger and continuous increase to 173 (A1) and 177 (A2) Tg N_r in 2045, and 214 (A1) and 260 (A2) Tg N_r in 2095 (Fig. 3). Despite these wide ranges, the differences of N_2O emissions between the scenarios is in the first half of the century rather narrow. They start with 3.9 Tg N_2O-N in 1995, with a range of 3.0 to 4.9 Tg N_2O-N being the 90 % confidence interval for uncertainty of the underlying emission parameters of Eggleston et al. (2006). Up to 2045, they rise to 7.2 (5.4 to 9.0) Tg N_2O-N in the B1 scenario and 8.6 (6.6 to 10.5) Tg N_2O-N in the A2 scenario, and widen towards the end of the century to 4.9 (3.5 to 6.4) Tg N_2O-N in the B1 scenario and 11.6 (8.8 to 14.2) Tg N_2O-N in the A2 scenario (Fig. 4).

3.2 Regional budgets

While the surge of the N_r cycle can be observed in all regions, the speed and characteristics are very different between regions (Table 2). Sub-Saharan Africa (AFR), South Asia (SAS), and Australia and Japan (PAO) show the strongest relative increases in harvested N_r, while in Europe (EUR) and North America (NAM) the increases are more modest. The

Table 2. Regional estimates of N_r flows for the state in 1995 and for the four scenarios $\frac{A1|B1}{A2|B2}$ in Tg N_r per year. Losses consist of losses from cropland soils and animal waste management.

N_r flow	Year	World		Regions: AFR		CPA		EUR		FSU		LAM		MEA		NAM		PAO		PAS		SAS	
Harvest	1995	63		3		12		10		5		6		2		13		2		3		7	
	2045	182	160	15	14	30	28	15	14	10	9	29	21	10	10	20	19	17	11	6	5	30	29
		153	143	12	12	26	28	15	14	9	9	22	19	8	7	23	20	10	7	6	5	21	22
	2095	196	137	20	9	33	27	16	13	11	8	26	13	14	12	21	17	18	7	5	3	33	29
		260	169	24	19	38	30	19	15	13	11	50	22	13	9	32	21	25	9	10	6	35	29
Residues	1995	35		3		6		4		3		4		1		6		1		2		5	
	2045	94	85	10	9	15	15	7	7	7	7	16	13	4	4	10	9	9	6	4	4	12	12
		73	67	8	7	12	13	6	6	4	4	11	9	3	2	10	8	5	3	4	3	11	10
	2095	98	76	11	7	17	15	7	6	8	7	15	9	5	5	11	9	8	3	4	3	13	12
		114	76	12	10	19	14	8	6	5	4	21	9	5	3	13	9	11	4	6	3	15	12
Fertilizer	1995	78		1		24		13		2		4		3		13		1		4		13	
	2045	173	145	9	7	40	36	13	13	11	9	6	7	15	14	23	21	33	19	5	3	20	15
		177	122	14	8	41	30	21	16	8	5	7	10	11	8	30	20	18	9	6	4	22	11
	2095	214	128	0	0	50	39	21	16	12	8	23	0	23	17	19	15	32	12	4	4	24	17
		260	131	19	10	59	35	22	15	10	7	20	5	12	9	37	20	46	12	7	5	27	12
Manure	1995	111		15		12		13		7		21		3		10		4		3		22	
	2045	241	217	65	60	28	22	20	15	8	7	63	55	7	7	9	6	3	2	6	5	32	39
		250	262	51	56	26	37	17	13	10	9	58	52	11	8	14	9	5	3	9	9	49	65
	2095	205	131	105	44	16	12	6	2	7	5	23	36	5	3	17	8	2	1	4	2	19	18
		332	240	69	69	34	26	21	10	11	5	92	51	20	11	17	5	5	1	12	7	50	55
Biol. N_r	1995	27		2		4		2		2		4		0		5		1		2		4	
	2045	72	61	8	7	8	7	5	4	4	4	17	11	1	1	8	7	2	2	4	2	17	16
		57	56	6	6	6	8	4	3	4	4	13	11	1	1	8	8	2	2	3	2	10	11
	2095	75	46	11	4	9	5	4	3	5	3	15	6	1	1	7	6	3	0	1	1	20	17
		95	64	12	8	7	7	4	4	5	6	30	12	3	2	11	8	3	2	4	2	17	14
Trade	1995	0		0		-1		-2		-1		2		-2		4		0		-1		0	
	2045	0	0	-8	-8	-1	3	-6	-3	1	1	-11	-14	-2	-1	10	11	14	8	-3	-2	9	6
		0	0	-3	-6	-4	-7	-1	1	1	2	1	3	-7	-4	10	11	7	4	-4	-4	1	0
	2095	0	0	-51	-21	16	14	6	7	1	0	4	-21	0	1	0	6	14	5	-3	-3	14	11
		0	0	-5	-15	-6	1	-2	4	1	6	-3	-8	-19	-6	15	14	20	8	-6	-3	4	-2
Losses	1995	109		5		27		15		9		8		3		18		3		7		15	
	2045	180	146	17	16	32	27	15	13	11	10	28	23	10	9	18	14	19	10	7	6	21	19
		201	137	18	14	37	31	21	14	11	8	27	16	10	7	27	16	13	6	10	7	25	18
	2095	197	103	39	11	31	20	14	8	12	7	23	14	14	8	19	11	18	5	6	3	21	15
		257	131	25	19	45	25	21	11	12	6	43	19	14	8	30	12	26	6	12	5	29	19
N_2O	1995	3.9		0.4		0.7		0.5		0.3		0.7		0.1		0.6		0.1		0.2		0.4	
	2045	8.1	7.2	1.4	1.3	1.1	1	0.6	0.5	0.4	0.3	1.8	1.6	0.4	0.4	0.6	0.5	0.6	0.4	0.3	0.2	0.9	0.9
		8.6	7.5	1.3	1.3	1.2	1.3	0.7	0.5	0.4	0.3	2	1.6	0.4	0.3	0.9	0.6	0.4	0.2	0.3	0.3	1	1
	2095	7.2	4.9	1.8	0.8	1	0.8	0.5	0.3	0.4	0.3	0.8	0.8	0.5	0.4	0.7	0.5	0.6	0.2	0.2	0.1	0.7	0.6
		11.6	7.2	1.7	1.5	1.5	1	0.8	0.5	0.4	0.3	2.9	1.5	0.6	0.4	1.1	0.5	0.9	0.3	0.4	0.2	1.2	1.1

increase in production in AFR is not sufficient to settle domestic demand, such that large amounts of N_r have to be imported from other regions. Also the Middle East and Northern Africa (MEA) have to import large amounts of N_r due to the unsuitable production conditions and high population growth. At the same time, AFR requires only low amounts of inorganic fertilizer, as the domestic livestock production fed with imported N_r provides sufficient nutrients for production. In the globalised scenarios A1 and B1, the overspill of manure even reduces the actual soil nutrient uptake efficiency (SNUpE) in 2095 with 0.41 (A1) and 0.67 (B1), below the potential scenario value of 0.6 or 0.7.

Despite its large increase in consumption, SAS does not require large imports, as it can also settle its N_r requirements with a balanced mix of biological fixation, manure, crop residues and inorganic fertilizer. Similarly, Latin America can cover large parts of its N_r demand with biological fixation and manure. In comparison with this, the large exporters North America (NAM) and Pacific OECD (PAO) have a much stronger focus on fertilization with inorganic fertilizers.

In the globalised scenarios, these characteristics tend to be more pronounced than in the regionalised scenarios, as each region specialises in its relative advantages. The structural differences between the economical and ecological oriented scenarios are less distinct, yet it can be observed that the reduced livestock consumption in developed regions leads to a lower importance of manure and a generally lower harvest of N_r in these regions.

4 Discussion

This study aims to create new estimates for the current state and the future development of the agricultural N_r cycle. For this purpose, we adapted the land-use model MAgPIE to calculate major agricultural N_r flows. As will be discussed in the following, the current size of the N_r cycle is much higher than previously estimated. The future development of the N_r cycle depends largely on the scenario assumptions, which we based on the SRES storylines (Nakicenovic et al., 2000). We expect the future rise of the N_r cycle to be higher than suggested by most other studies. Thereby, the livestock sector dominates both the current state and future developments. The surge of the N_r cycle will most likely be accompanied by higher N_r pollution.

4.1 The current state of the agricultural N_r cycle

Data availability for N_r flows is poor. Beside the consumption of inorganic fertilizer, no N_r flow occurs in official statistics. Even the underlying material flows, like production and use of crop residues or animal manure are usually not recorded in international statistics. Therefore, independent model assessments are required, using different methodologies and parametrisations to identify major uncertainties. In the following we compare our results mainly with estimates of Smil (1999), Sheldrick et al. (2002) and Liu et al. (2010a), as summarised in Table 3.

The estimates for N_r withdrawals by crops and aboveground residues are relatively certain. They have now been estimated by several studies using different parametrisations. The scope between the studies is still large with 50 to 63 Tg N_r for harvested crops and 25 to 38 Tg N_r for residues, whereby the estimate of Sheldrick et al. (2002) may be too high due to the missing correction for dry matter when estimating nitrogen contents (Liu et al., 2010b).

Large uncertainties can be attributed to the cultivation of fodder and cover crops. They represent a substantial share of total agricultural biomass production, and they are rich in N_r and often N_r fixers. Yet, the production area, the species composition and the production quantity are highly uncertain, and no reliable global statistics exist. The estimate from FAOSTAT (2005) used by our study has been withdrawn without replacement in newer FAOSTAT releases. It counts 2900 Tg fresh matter fodder production on 190 million ha (Mha). Smil (1999) appraises the statistical yearbooks of 20 large countries and provides a lower estimate of only 2500 Tg that are produced on 100–120 Mha.

Estimates for N_r in animal excreta diverge largely in the literature. Using bottom-up approaches based on typical excretion rates and N_r content of manure, Mosier et al. (1998) and Bouwman et al. (2011) calculate total excretion to be above 100 Tg N_r. Smil (1999) assumes total excretion to be significantly lower with only 75 Tg N_r. Our top-down approach, using the fairly reliable feed data of the FAOSTAT database, can support the higher estimates of Mosier et al. (1998) and Bouwman et al. (2011), with an estimate of 111 Tg N_r. The same global total of 111 Tg N_r can be obtained bottom-up if one multiplies typical animal excretion rates taken from Eggleston et al. (2006) with the number of living animals (FAOSTAT, 2011). Yet, regional excretion rates diverge significantly; the top-down approach leads to considerably higher rates in Africa and the Middle East and lower rates in South and Pacific Asia.

Biological N_r fixation is another flow of high uncertainty and most studies still use the per ha fixation rates of Smil (1999) for legumes, sugarcane and free-living bacteria. Currently no better estimate exists for free-living bacteria (Herridge et al., 2008). However, they contribute only a minor input to the overall N_r budget with little impacts on our model results. To estimate the fixation by legumes and sugarcane, we use a new approach based on percentages of plant N_r derived from fixation, similar to Herridge et al. (2008). This, in combination with total above- and belowground N_r content of a plant, can predict N_r fixation more accurately. However, the parametrisation of Herridge et al. (2008) probably overestimates N_r fixation, especially for soybeans. Most importantly, the N_r content of the belowground residues as well as the shoot : root ratio seem too high when comparing them with Eggleston et al. (2006), Sivakumar et al. (1977) or Dogan et al. (2011). Also the N_r content of the shoot seems too high given that soybean residues have a much lower N_r content than the beans (Fritsch, 2007; Wirsenius, 2000; Eggleston et al., 2006). Correcting the estimates of Herridge et al. (2008) for the water content of the harvested crops further reduces their estimate. If one finally accounts for the difference in base year between the two estimates, with global soybean production increasing by 69 % between 1995 and 2005, we come to a global total fixation from legumes and sugarcane of 9 Tg N_r in 1995 as opposed to 21 Tg N_r in 2005 in the case of Herridge et al. (2008). Our estimate is in between the estimates of Smil (1999) and Sheldrick et al. (2002), even though we used a different approach.

Accumulation or depletion of N_r in soils has so far been neglected in future scenarios (Bouwman et al., 2009, 2011), assuming that soil organic matter is stable and all excessive N_r will volatilise or leach. However, the assumption of a steady state for soil organic matter should not be valid for land conversion or for the cultivation of histosols. Our rough bottom-up calculations estimate that the depletion of soil organic matter after transformation of natural vegetation or pasture to cropland releases 25 Tg N_r per year. With a yearly global average release of 122 kg N_r per ha newly converted cropland, the amount of N_r released may exceed the nutrients actually required by the crops, especially in temperate, carbon rich soils. Vitousek et al. (1997) estimates that the cultivation of histosols and the drainage of wetlands releases another 10 Tg N_r per year, although it is unclear how much thereof enters agricultural systems.

The total size of the cropland N_r budget is larger than estimated by previous studies. This can be attributed less to a correction of previous estimates than to the fact that past studies did not cover all relevant flows. In Table 3 we summarise cropland input and withdrawals mentioned by previous studies. The sum of all withdrawals (Total OUT) ranges between 81 and 115 Tg N_r. However, if the unconsidered flows are filled with estimates from other studies, the corrected withdrawals (Total OUT*) shifts to 105–134 Tg N_r. The same applies to inputs, where the range shifts and narrows down from 137–205 Tg N_r total inputs (Total IN) to 198–232 Tg N_r total inputs when all data gaps are filled (Total IN*). The N_r uptake efficiency (NUpE*), defined as the fraction of IN* which is incorporated into OUT* remains within the plausible global range of 0.35–0.65 defined by Smil (1999) for all studies. In our study, this holds even for every MAgPIE world region. SNUpE and SNUpE* are slightly higher, with 49 % and 51 % of N_r applied to soils being taken up by the roots of crops. The corrected estimates for total losses (Losses*) is, with 84–112 Tg N_r, significantly higher than previously estimated.

Table 3. Comparison of global cropland soil balances.

	This study	Smil (1999b)	Sheldrick (1996)	Liu (2010)
Base year	1995	1995	1996	2000
OUT				
Crops	50	50	63	52
Crop residues	31	25	38	29
Fodder	13	10	–	–
Fodder residues	4	–	–	–
BG residues	17	–	–	–
IN				
Residues	12	14	23	11
Fodder residues	4	–	–	–
BG residues	17	–	–	–
Legume fixation	9	10	8	22
Other fixation	10	11	–	
Fixation fodder	11	12	–	–
Atm. deposition	15	20	22	14
Manure on field	24	18	25	17
Seed	2	2	–	–
Irrigation water	–	4	–	3
Sewage	–	–	3	–
Soil organic matter loss	25	–	–	–
Fertilizer	78	78	78	68
Histosols	–	–	–	–
BALANCE				
Total OUT	115	85	101	81
Total OUT*	115	105	134	114
Total IN	205	169	159	137
Total IN*	212	217	232	198
Losses	91	80	75	67
Losses*	98	112	97	84
NUpE	0.56	0.50	0.64	0.59
NUpE*	0.54	0.48	0.58	0.58
SNUpE	0.51	0.42	0.62	0.51
SNUpE*	0.49	0.42	0.54	0.48

*Data gaps are filled with estimates from other studies. We use estimates by this study if available; for irrigation we use Smil (1999), for sewage Sheldrick et al. (2002), and for histosols no estimate exists.

4.2 Scenario assumptions

The simulation of the widely used SRES storylines (Nakicenovic et al., 2000) facilitates the comparison with other studies like Bouwman et al. (2009) or Erisman et al. (2008) and allows for the integration of our results into other assessments. However, the SRES storylines provide only a qualitative description of the future. In the following, the key assumptions underlying our parametrisation and model structure shall be discussed.

All SRES storylines tend to assume a continuation of current trends, without external shocks or abrupt changes of dynamics. They merely diverge in the interpretation of past dynamics or the magnitude of change assigned to certain trends. Population grows at least until the mid of the 21st century, and declines first in developed regions. Per-capita income grows throughout the century in all scenarios and all world regions, and developing regions tend to have higher growth rates than developed regions. This has strong implications on the food demand, which is driven by both population and income growth. As food demand is a concave function of income, it depends mostly on the income growth in low-income regions. In the first half of the century, the pressure from food demand is therefore highest in the high-income A1 scenario. In the second half, the A2 scenario also reaches a medium income and therefore a relatively high per capita food demand. Additionally, the population growth diverges between the scenarios in the second half of the century, with the A2 scenario reaching the highest world population and as a consequence the highest food demand. As food demand is exogenous to our model, price effects on consumption are not captured by the model. However, even in the A2 scenario the shadow prices (Lagrange multipliers) of our demand constraints increase globally by 0.5 % per year until 2045, with no region showing higher rates than 1.1 %. This indicates only modest price pressure, lagging far behind income growth.

Concerning the productivity of the livestock sector, we assume that the feed required to produce one ton of livestock product is decreasing in all scenarios, even though at different rates. Starting from a global level of 0.62 kg N in feed per ton livestock product dry matter, the ratio decreases to 0.4 (A1) or 0.52 (B2) in 2095 (see Supplement). A critical aspect is that as all regions converge towards the European feed baskets, no productivity improvements beyond the European level take place. Beside the improvement of feed baskets, the amount of feed is also determined by the mix of livestock products, with milk and eggs requiring less N_r in feed than meat. As we could not find a historical trend in the mix of products (FAOSTAT, 2011), we assumed that current shares remain constant in the future. This causes continuing high feeding efficiencies in Europe and North America, where the share of milk and non-ruminant meat is high.

As we calculate our livestock excretion rates based on the feed mix, the increased feeding efficiency also translates into lower manure production per ton livestock product. At the same time, our scenario assumptions of an increasing share of either anaerobic digesters or daily spread in manure management also lead to higher recycling rates of manure excreted in confinement. Even though with increasing development an increasing share of collected manure is applied also to pastureland as opposed to cropland, the amount of applied manure N_r per unit crop biomass remains rather constant. Due to the increasing N_r efficiency, its ratio relative to other N_r inputs like inorganic fertilizers increases.

Our closed budget approach to calculate future inorganic fertilizer consumption is based on the concept of cropland soil N_r uptake efficiency (SNUpE). Other indicators of N_r efficiency relate N_r inputs to crop biomass. They include for example N_r use efficiency (NUE), defined as grain dry matter divided by N_r inputs (Dawson et al., 2008), and agronomic efficiency of applied N_r (AE_N), defined as grain dry matter increase divided by N_r fertilizer (Dobermann, 2005). Compared to these indicators, N_r uptake efficiency (NUpE) indicates the share of all N_r inputs that is incorporated into plant biomass (Dawson et al., 2008). Under the condition that all N_r inputs (including the release of soil N_r) are accounted for, this share has the advantage of an upper physical limit of 1. N_r withdrawals cannot exceed N_r inputs. At the same time, this indicator reveals the fraction of losses connected to the application of N_r inputs. SNUpE is similar to NUpE, but regards only soil inputs and withdrawals and excludes seed N_r as well as internal biological fixation from legumes and sugarcane. Prior to the uptake by the plant, these inputs are not subject to leaching and volatilisation losses (Eggleston et al., 2006), and denitrification losses are also inconsiderable (Rochette and Janzen, 2005). Therefore, one regional value of SNUpE suffices to simulate that NUpE of N_r fixing crops is higher compared to the NUpE of normal crops (Peoples and Herridge, 1990).

The level of SNUpE is in our model an exogenous scenario parameter for future simulations which has a large impact on the estimates of inorganic fertilizer consumption and N_2O emissions. If SNUpE would be 5 percentage points lower, fertilizer consumption would increase by 8 to 10 % in 2045, depending on the scenario. At the same time, total agricultural N_2O emissions would increase by 11 to 15 %. If fertilizer efficiency would increase by 5 percentage points, fertilizer consumption would fall by 7 to 8 % and emissions would decrease by 9 to 13 %. As the magnitude of N_r flows is higher in some scenarios, a ± 5 % variation of SNUpE translates in the A1 scenario into a change of fertilizer consumption of -32 to $+37$ Tg N_r and a change of -1.1 to $+1.3$ Tg N_2O-N of emissions in 2045, while in the B2 scenario fertilizer changes only by -20 to $+24$ Tg N_r and emissions by -0.7 to $+0.8$ Tg N_2O-N.

The future development of SNUpE is highly uncertain. It depends on numerous factors, most importantly on the management practices like timing placing and dosing of fertilizers and the use of nutrient trap crops. Also, a general improvement of agricultural practices like providing adequate moisture and sufficient macro- and micronutrients, pest control and avoiding soil erosion can contribute their parts. Finally, climate, soils, crop varieties and the type of nutrient inputs also influence N_r uptake efficiency. The complexity of these dynamics and the numerous drivers involved still do not allow making long-term model estimates for N_r efficiencies, but this should be a target for future research.

Meanwhile, we use SNUpE as an explicitly defined scenario parameter. As it descriptively indicates the share of losses, and as the theoretical upper limit of 1 is clearly fixed, it makes our model assumptions transparent and easily communicable. Our assumptions concerning the development of SNUpE are rather optimistic. In 1995, none of the 10 world regions reached a SNUpE of 60 %, and four regions (CPU, FSU, PAS, SAS) were even below 50 %. The current difference between the region with the lowest SNUpE (CPA with 43 %) and the region with the highest SNUpE (EUR with 57 %) is thereby still lower than the difference of EUR and our scenario parameter of 70 % for the environmentally oriented scenarios.

We assumed that trade liberalisation continues in all scenarios, even though at different paces. The trade patterns diverge strongly between the scenarios, even though certain dynamics persist. Sub-Saharan Africa, Europe and Latin America tend to become livestock exporting regions, while South, Central and Southeast Asia as well as the Middle East and Northern Africa become importers of livestock products. On the other hand, sub-Saharan Africa and Pacific Asia become importers of crop products, while the former Soviet Union and Australia become exporters of crops. Trade dynamics in MAgPIE are determined partly on the basis of historical trade patterns, partly by competitiveness. However, certain other dynamics that are of great importance in reality, most importantly political decisions like tariffs or export subsidies, are not represented explicitly in the model. Due to the uncertainty regarding trade patterns, regional production estimates are therefore of higher uncertainty than global estimates. Trade patterns have strong implications on the N_r cycle. As soon as two regions are trading, the fertilizer consumption also shifts from the importing to the exporting region. Even more, sub-Saharan Africa currently imports crops and exports livestock products. Livestock fed with imported crops contributes in the form of manure to the cropland soil budgets and facilitates sub-Saharan Africa to use little inorganic fertilizer. Also in our future scenarios, the African livestock sector is very competitive and the inorganic fertilizer consumption does not increase until the mid of the century. A similar dynamic can be observed in Latin America, where inorganic fertilizer consumption also stays rather low.

In our environmentally oriented scenarios B1 and B2, vulnerable ecosystems are protected from land expansion. However, these protection schemes are assumed to be implemented gradually until 2045 and include only some of the most vulnerable forest areas. Large forest areas are still cleared in the beginning of the century, most importantly in the Congo river basin and the southern part of the Amazonian rainforest. Due to the land restrictions in the B scenarios, crop yields have to increase faster to be able to settle the demand with the available cropland area.

4.3 The future expansion of the N_r cycle

The size of the agricultural N_r cycle has increased tremendously since the industrial revolution. While in 1860 agriculture fixed only 15 Tg N_r (Galloway et al., 2004), in 1995 the Haber–Bosch synthesis, biological fixation and soil organic matter loss injected 133 Tg new N_r into the N_r cycle. Our scenarios suggest that this surge will persist into the future, and will not stop before the middle of this century. The development is driven by a growing population and a rising demand for food with increasing incomes, along with a higher share of livestock products within the diet. The N_r in harvested crops may more than triple. Fixation by inorganic fertilizers and legumes as well as recycling in the form of crop residues and manure may also increase by a factor of 2–3.

Our top-down estimates of future animal excreta are higher than the bottom-up estimates by Bouwman et al. (2011). In our scenarios, N_r excretion rises from 111 Tg N_r in 1995 to 217 Tg N_r (B1)–262 Tg N_r (A1) in 2045. Bouwman et al. (2011) estimate that N_r excretion increases from 102 Tg N_r in 2000 to 154 Tg N_r in 2050. These differences are caused by diverging assumptions. Firstly, while Bouwman et al. (2011) assume an increase of global meat demand by 115 % within 50 yr, our study estimates an increase by 136 % (A2)–200 % (A1). Secondly, Bouwman et al. (2011) assume rising N_r excretion rates per animal for the past, but constant rates for the future, such that weight gains of animals are not connected to higher excretion rates. As the current excretion rates in developing regions are still lower than in developed regions (IPCC, 1996), this assumption will underestimate the growth of excretion rates in developing regions. Our implementation calculates excretion rates based on the feed baskets and the N_r in livestock products. Under the assumption that developing regions increasingly adopt the feeding practices of Europe, this top-down approach results in increasing excretion rates per animal in developing regions. However, as we assume no productivity improvements in developed regions, we tend to overestimate future manure excretion in developed regions.

N_r release from soil organic matter (SOM) loss contributes to the N_r budget also in the future, yet with lower rates. In the environmentally oriented B scenarios, cropland expansion and therefore also SOM loss almost ceases due to forest protection, while in the economically oriented scenarios, the loss of SOM still contributes 10 (A1) and 18 (A2) Tg N_r per year. In the A2 scenario the loss even continues at low rates until the end of the century. The reduced inputs of soil organic matter loss have to be replaced by inorganic fertilizers.

Our estimates of inorganic fertilizer consumption are within the range of previous estimates. Figure 3 compares our results to estimates by Daberkow et al. (2000), Davidson (2012), Erisman et al. (2008), Tilman et al. (2001), Tubiello and Fischer (2007) and Bouwman et al. (2009). The differences in estimates is enormous, ranging in 2050 from 68 (Bouwman et al., 2009) to 236 Tg N_r (Tilman et al., 2001). In contrast to Bouwman et al. (2009) and Erisman et al. (2008), who also created scenarios based on the SRES storylines, our highest estimate is the A2 scenario, while the other two models have the A1 scenario as highest scenario. Also, our scenarios have in general a higher fertilizer consumption, especially compared to Bouwman et al. (2009). This may be

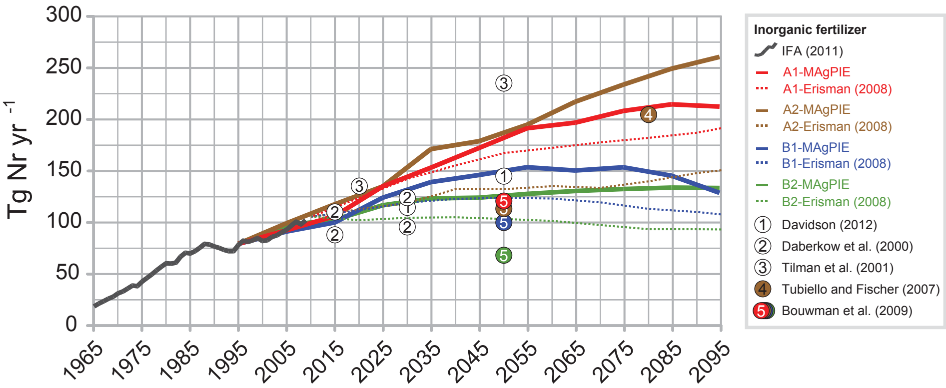

Fig. 3. Fertilizer consumption: historic dataset of IFADATA (2011), SRES scenario estimates by Erisman et al. (2008), Bouwman et al. (2009), Tubiello and Fischer (2007) and our study, as well as other estimates by Davidson (2012), Daberkow et al. (2000) and Tilman et al. (2001).

rooted in a different scenario parametrisation and a different methodological approach: Our scenarios assume a strong demand increase also for relatively low income growth as we explained in Sect. 4.2. At the same time, low income growth goes along with slow efficiency improvements in production. The combined effects explain the strong rise of inorganic fertilizer consumption in the A2 scenario. At the same time, our estimates are based on a top-down approach, compared to the bottom-up approach of Bouwman et al. (2009, 2011) or Daberkow et al. (2000). Both approaches have advantages and disadvantages. Data availability for bottom-up estimates of fertilizer application is currently poor, and may be biased by crop-rotations and different manure application rates. Our top-down approach has the disadvantage that it has to rely on an exogenous path for the development of N_r uptake efficiency. Also, as the closing entry of the budget, it accumulates the errors of other estimated N_r flows. But the top-down approach has the advantage that it can consistently simulate substitution effects between different N_r sources or a change in crop composition. This is of special importance if one simulates large structural shifts in the agricultural system like an increasing importance of the livestock sector.

Data on historic fertilizer consumption is provided by IFADATA (2011) and FAOSTAT (2011). Both estimates diverge, as they use different data sources and calendar years. On a regional level, differences can be substantial. FAO's estimate for fertilizer consumption in China in the year 2002 is 13 % higher than the estimate by IFA. As IFADATA (2011) provides longer continuous time series, we will refer to this dataset in the following. Fertilizer consumption between 1995 and 2009 (IFADATA, 2011) grows by +1.8 % per year. The estimates of Daberkow et al. (2000) and Bouwman et al. (2009, 2011) show lower growth rates of −0.4 % to +1.7 % over the regarded period of 20 to 50 yr. Our 50 yr average growth rate also stays with +0.9 % (B1) to +1.7 % (A2) below the observations. Yet, our short-term growth rate from 1995 to 2005 captures the observed development with a range of +1.5 % (B1) to +2.4 % (A2) between the scenarios. Due to trade our regional fertilizer projections are more uncertain than the global ones (see Sect. 4.2). Our results still meet the actual consumption trends of the last decades for most regions. However, fertilizer consumption in India rises slower than in the past or even stagnates, while the Pacific OECD region shows a strong increase in fertilizer consumption.

The range of our scenario outcomes is large for all N_r flows, and continues to become larger over time. It can be observed that the assumptions on which the globalised and environmentally oriented scenarios are based lead to a substantially lower turnover of the N_r cycle than the regional fragmented and economically oriented scenarios.

4.4 The importance of the livestock sector

The agricultural N_r cycle is dominated by the livestock sector. According to our calculations, livestock feeding appropriates 40 % (25 Tg) of N_r in global crop harvests and one third (11 Tg) of N_r in aboveground crop residues. Conversion byproducts add another 13 Tg N_r to the global feed mix. Moreover, 70 Tg N_r may be grazed by ruminants on pasture land, even though this estimate is very uncertain due to poor data availability on grazed biomass and N_r content of grazed pasture. The feed intake of 123 Tg results in solely 8 Tg N_r in livestock products.

In developed countries, the relative share of animal calories in total consumption already declined in the last decades. However, developing and transition countries still feature a massive increase in livestock consumption (FAOSTAT, 2011). According to our food demand projections, the rising global demand for livestock products will not end before the middle of the century. In the second half of the century, both an upward or a downward trend is possible.

More efficient livestock feeding will not necessarily relieve the pressure from the N_r cycle. Although the trend towards energy efficient industrial livestock feeding may reduce the demand for feed, this also implies a shift from pasture grazing, crop residues and conversion byproducts towards feedstock crops. Pasture grazing and crop residues do not have the required nutrient-density for highly productive livestock systems (Wirsenius, 2000). According to our calculations, conversion byproducts today provide one fourth of the proteins fed to animals in developed regions. Latin America exports twice as much N_r in conversion byproducts as in crops. At the same time, Europe cannot settle its conversion byproduct demand domestically. Conversion byproducts will not be sufficiently available if current industrialised feeding practices are adopted by other regions. The feedstock crops required to substitute conversion byproducts, pasture and crop residues will put additional pressure on the cropland N_r flows. The pressure on pasture however will most likely be only modest.

4.5 The future expansion of N_r pollution

All N_r that is not recycled within the agricultural sector is a potential environmental threat. Bouwman et al. (2009) estimate that over the next 50 yr, only 40–60 % of the lost N_r will be directly denitrified. The remaining N_r will either volatilise in the form of N_2O, NO_x and NH_y or leach to water bodies. With the surge of the N_r cycle, air, water and atmospheric pollution will severely increase, which has strong negative consequences for human health, ecosystem services and the stability of ecosystems.

Along with local and regional impacts, it is still under debate whether a continuous accumulation of N_r could destabilize the earth system as a whole (Rockström et al., 2009a,b). While there is little evidence supporting abrupt changes on a global level, N_r pollution contributes gradually to global phenomena such as biodiversity loss, ozone depletion and global warming. For the latter two, N_2O emissions play a crucial role. N_2O, is currently the single most important ozone depleting substance, as it catalyses the destruction of stratospheric ozone (Ravishankara et al., 2009). In addition, N_2O has an extraordinarily long atmospheric lifetime and absorbs infrared radiation in spectral windows not covered by other greenhouse gases (Vitousek et al., 1997). Fortunately, the greenhouse effect of N_2O might be offset by NO_x and NH_y emissions. By reducing the atmospheric lifetime of CH_4, scattering light and increasing biospheric carbon sinks, these emissions have a cooling effect (Butterbach-Bahl et al., 2011).

According to our calculations, N_2O emissions from managed soils and manure contributed 3.9 Tg N_2O-N, or approximately half of total anthropogenic N_2O emissions (Vuuren et al., 2011). However, the uncertainty involved is high. The result of our Monte Carlo variation of the emission parameters suggests that the emissions may lie with a 90 % probability in the range of 3.0 to 4.9 Tg N_2O-N. This only covers parts of the uncertainty, as the underlying activity data is also uncertain. Finally, actual agricultural emissions should be slightly higher than our estimate, as we do not cover all agricultural N_2O emission sources of the National Greenhouse Gas Inventories (Eggleston et al., 2006) and as also these inventories have no full coverage. Crutzen et al. (2008), using a top-down approach, estimate total agricultural N_2O emissions in 2000 to be in the range of 4.3 to 5.8 Tg N_2O-N, which is modestly higher than our estimate of 3.4 to 5.5 (90 % confidence, mean: 4.4) Tg N_2O-N in the year 2000.

Compared to the SRES marker scenarios (Nakicenovic et al., 2000), our results suggest that emissions will increase with substantially higher growth rates in the first half of the century. Especially in the case of the A1 and B2 scenarios, we come to 66 % (A1) and 36 % (B2) higher cumulative emissions over the century. In scenario A2 our estimates are continuously approximately 20 % lower (A2), while in the B1 scenario cumulative emissions are 6 % higher (B1) but occur later in the century (Fig. 3). None of our agricultural N_2O emission scenarios would be compatible with the RCP2.6 scenario, which keeps the radiative forcing below 2.6 $\frac{W}{m^2}$ in 2100 (Moss et al., 1998). To reach a sustainable climate target, explicit GHG mitigation efforts would therefore be required even in optimistic scenarios. If the non-agricultural N_2O emissions grow in similar pace than agricultural N_2O emissions, the A2 scenario might even outpace the RCP8.5 scenario.

In the beginning of the century, the uncertainty of emission parameters is much larger than the spread of scenario mean values. Only in the second half of the century, the differences of the scenarios are of similar magnitude to the emission parameter uncertainty. While the scenarios are just representative pathways and have no pretension to cover a specific probability space, this still indicates that a better representation of the underlying biophysical processes would largely improve our emission estimates.

5 Conclusions

The current state of the global agricultural N_r cycle is highly inefficient. Only around half of the N_r applied to cropland soils is taken up by plants. Furthermore, only one tenth of the N_r in cropland plant biomass and grazed pasture is actually consumed by humans. During the 21st century, our scenarios indicate a strong growth of all major flows of the N_r cycle. In the materialistic, unequal and fragmented A2 scenario, inorganic fertilizer consumption more than triples due to a strong population growth and slow improvement in N_r efficiencies in livestock and crop production. In the prosperous and materialistic A1 scenario, the strong increase of livestock consumption in the first half of the century and the industrialisation of livestock production quadruple the demand for N_r in feed crops already in 2045. In the heterogeneous,

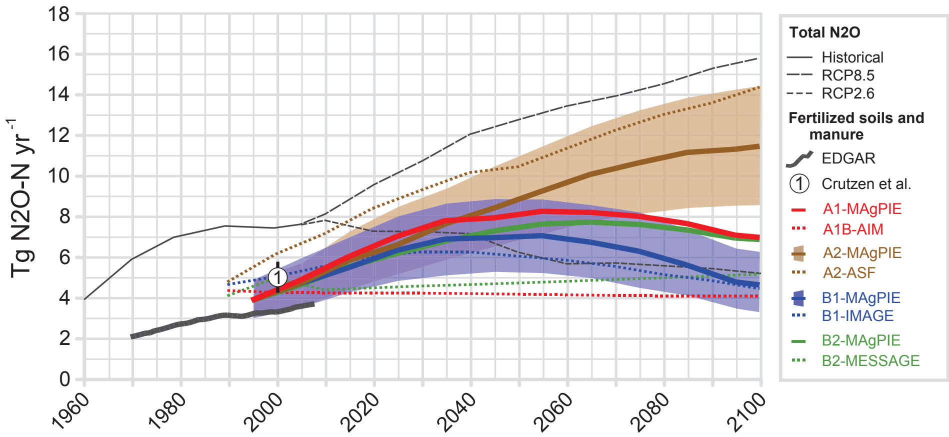

Fig. 4. Total anthropogenic N_2O emissions: historic emissions, highest and lowest RCP scenarios (Vuuren et al., 2011). N_2O emissions from soils and manure: historic estimates for 1970–2008 of the EDGAR 4.2 database (EC-JRC/PBL, 2011), a top-down estimate by Crutzen et al. (2008) for the year 2000, the SRES marker scenarios (Nakicenovic et al., 2000) for 1990–2100 and our scenarios for the SRES storylines for 1995–2095. The shaded areas represent a 90 % probability range in respect to the uncertainty of emission parameters of our A2 and B1 scenarios. Our A1 and B2 scenarios have a similar relative uncertainty range.

environmentally oriented B2 scenario, food demand is lower, especially in the first half of the century. However, the livestock sector productivity is improving only slowly and requires high amounts of N_r in feed. Finally, even in the globalised, equitable, environmental B1 scenario, N_r in harvested crops more than doubles and fertilizer consumption increases by 60 % and emissions by 23 % until the end of the century, with a peak in the middle of the century. In this scenario, the low meat consumption and large N_r efficiency improvements both in livestock and crop production are outbalanced by population growth and the catch-up of the less developed regions with the living standard of the rich regions.

Losses to natural systems will also continuously increase. This has negative consequences on both human health and local ecosystems. Moreover, it threatens the earth system as a whole by contributing to climate change, ozone depletion and loss of biodiversity. N_r mitigation is therefore one of the key global environmental challenges of this century.

Our model of the agricultural sector as a complex interrelated system shows that a large variety of dynamics influence N_r pollution. Each process offers a possibility of change, such that mitigation activities can take place not only where pollution occurs physically, but on different levels of the agricultural system: (a) already at the household level, the consumer has the choice to lower his N_r footprint by replacing animal with plant calories and reducing household waste (Popp et al., 2010; Leach et al., 2012); (b) substantial wastage during storage and processing could be avoided (Gustavsson et al., 2011); (c) information and price signals on the environmental footprint are lost within trade and retailing, such that sustainable products do not necessarily have a market advantage (Schmitz et al., 2012); (d) livestock products have potential to be produced more efficiently, both concerning the amount of N_r required for one ton of output and the composition of feed with different N_r footprints; (e) higher shares of animal manure and human sewage could be returned to farmlands (Wolf and Snyder, 2003); (f) nutrient uptake efficiency of plants could be improved by better fertilizer selection, timing and placing, as well as enhanced inoculation of legumes (Herridge et al., 2008; Roberts, 2007); (g) finally, unavoidable losses to natural systems could be directed or retained to protect vulnerable ecosystems (Jansson et al., 1994).

Appendix A

Extended methodology

A1 Model of Agricultural Production and its Impact on the Environment (MAgPIE): general description

MAgPIE is a global land-use allocation model which is linked with a grid-based dynamic vegetation model (LPJmL) (Bondeau et al., 2007; Sitch et al., 2003; Gerten et al., 2004; Waha et al., 2012). It takes into account regional economic conditions as well as spatially explicit data on potential crop yields and land and water constraints, and derives specific land-use patterns, yields and total costs of agricultural production for each grid cell. The following will provide only a brief overview of MAgPIE, as its implementation and validation is presented in detail elsewhere (Lotze-Campen et al., 2008; Popp et al., 2010, 2012; Schmitz et al., 2012).

The MAgPIE model works on three different levels of disaggregation: global, regional, and cluster cells. For the model-runs of this paper, the lowest disaggregation level contains 500 cluster cells, which are aggregated from 0.5 grid cells based on an hierarchical cluster algorithm (Dietrich, 2011). Each cell has individual attributes concerning the available agricultural area and the potential yields for 18 different cropping activities derived from the LPJmL model. The geographic grid cells are grouped into ten economic world regions (Fig. 1). Each economic region has specific costs of production for the different farming activities derived from the GTAP model (Schmitz et al., 2010).

Food demand is inelastic and exogenous to the model, as described in further detail in the Sect. A4. Demand distinguishes between livestock and plant demand. Each calorie demand can be satisfied by a basket of crop or livestock products with fixed shares based on the historic consumption patterns. There is no substitution elasticity between the consumption of different crop products.

The demand for livestock calories requires the cultivation of feed crops. Weindl et al. (2010) uses a top-down approach to estimate feed baskets from the energy requirements of livestock, dividing the feed use from FAOSTAT (2011) between the five MAgPIE livestock categories.

Two virtual trading pools are implemented in MAgPIE which allocate the demand to the different supply regions. The first pool reflects the situation of no further trade liberalisation in the future and minimum self-sufficiency ratios derived from FAOSTAT (2011) are used for the allocation. Self-sufficiency ratios describe how much of the regional agricultural demand quantity is produced within a region. The second pool allocates the demand according to comparative advantage criteria to the supply regions. Assuming full liberalisation, the regions with the lowest production costs per ton will be preferred. More on the methodology can be found in Schmitz et al. (2012).

The non-linear objective function of the land-use model is to minimise the global costs of production for the given amount of agricultural demand. For this purpose, the optimization process can choose endogenously the share of each cell to be assigned to a mix of agricultural activities, the share of arable land left out of production, the share of non-arable land converted into cropland at exogenous land conversion costs and the regional distribution of livestock production. Furthermore, it can endogenously acquire yield-increasing technological change at additional costs (Dietrich, 2011). For future projections, the model works in time steps of 10 yr in a recursive dynamic mode, whereby the technology level of crop production and the cropland area is handed over to the next time step.

The calculations in this paper are created with the model-revision 4857 of MAgPIE. While a mathematical description of the core model can be found in the Supplement, the following Sects. A2, A3 and A4 explain the model extensions which are implemented for this study. The interface between the core model and the nutrient module consists of cropland area ($X^{\text{area}}_{t,j,v,w}$), crop and livestock dry-matter production ($\mathrm{P}(x_t)^{\text{prod}}_{t,i,k}$) and its use ($\mathrm{P}(x_t)^{\text{ds}}_{t,i,k,u}$). All parameters are described in Table A2. The superscripts are no exponents, but part of the parameter name. The arguments in the subscripts of the parameters include most importantly time (t), regions (i), crop types (v) and livestock types (l) (Table A1).

A2 Crop residues and conversion byproducts

A2.1 Crop residues

Eggleston et al. (2006) offer one of the few consistent datasets to estimate both aboveground (AG) and belowground (BG) residues. Also, by providing crop-growth functions (CGF) instead of fixed harvest indices, it can well describe current international differences of harvest indices and also their development in the future. The methodology is thus well eligible for global long-term modelling. Eggleston et al. (2006) provide linear CGFs with positive intercept for cereals, leguminous crops, potatoes and grasses. As no values are available for the oilcrops rapeseed, sunflower, and oilpalms as well as sugar crops, tropical roots, cotton and others, we use fixed harvest indices for these crops based on (Wirsenius, 2000; Lal, 2005; Feller et al., 2007). If different CGFs are available for crops within a crop group, we build a weighted average based on the production in 1995. The resulting parameters $r^{\text{cgf\_i}}_v$, $r^{\text{cgf\_s}}_v$ and $r^{\text{cgf\_r}}_v$ are displayed in Table A3. The AG crop residue production $\mathrm{P}(x_t)^{\text{prod\_ag}}_{t,i,v}$ is calculated as a function of harvested production $\mathrm{P}(x_t)^{\text{prod}}_{t,i,v}$ and the physical area $X^{\text{area}}_{t,j,v,w}$, and BG crop production as a function of total aboveground biomass.

$$\mathrm{P}(x_t)^{\text{prod\_ag}}_{t,i,v} := \sum_{j\in I_i,w} X^{\text{area}}_{t,j,v,w} \cdot r^{\text{cgf\_i}}_v + \mathrm{P}(x_t)^{\text{prod}}_{t,i,v} \cdot r^{\text{cgf\_s}}_v \tag{A1}$$

$$\mathrm{P}(x_t)^{\text{prod\_bg}}_{t,i,v} := (\mathrm{P}(x_t)^{\text{prod}}_{t,i,v} + \mathrm{P}(x_t)^{\text{prod\_ag}}_{t,i,v}) \cdot r^{\text{cgf\_r}}_v \tag{A2}$$

While it is assumed that all BG crop residues remain on the field, the AG residues are assigned to four different categories: feed, on-field burning, recycling and other uses. Residues fed to livestock ($\mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,v,\text{feed}}$) are calculated based on livestock production and livestock and regional specific residue feed baskets $r^{\text{fb\_ag}}_{t,i,l,v}$ from Weindl et al. (2010). The demand rises with the increase in livestock production $\mathrm{P}(x_t)^{\text{prod}}_{t,i,l}$ and can be settled either by residues $\mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,v,\text{feed}}$ or by additional feedstock crops $\mathrm{P}(x_t)^{\text{ds}}_{t,i,l,v,\text{sag}}$. The latter prevents that crops are produced just for their residues.

$$\sum_v \mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,v,\text{feed}} = \sum_{l,v} (\mathrm{P}(x_t)^{\text{prod}}_{t,i,l} \cdot r^{\text{fb\_ag}}_{t,i,l,v} - \mathrm{P}(x_t)^{\text{ds}}_{t,i,l,v,\text{sag}}) \tag{A3}$$

Residue burning ($\mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,v,\text{burn}}$) is fixed to 15 % of total AG crop residue dry matter in developed and 25 % in developing

Table A1. Attributes.

Set	Description	Elements
t	timesteps	y1995 (1), y2005 (2) .. y2095 (11)
i	economic world regions	AFR, CPA, EUR, FSU, LAM, MEA, NAM, PAO, PAS, SAS (Fig. 1)
j	cells, each assigned to a region i ($I_{AFR}=\{1..30\}$,...)	1:300
w	irrigation	irrigated, rainfed
v	crops	temperate cereals, maize, tropical cereals, rice, soybeans, rapeseed, groundnut, sunflower, oilpalm, pulses, potatoes, tropical roots, sugar cane, sugar beet, fodder crops, fibres, others
l	livestock	ruminant livestock, non-ruminant livestock, poultry, eggs, milk
k	products	$v \cup l$
f	feeding systems	grazing on cropland (grazc), grazing on pasture (grazp), animal houses (house)
c	animal waste management systems	anaerobic lagoons, liquid/slurry, solid storage, daily spread, anaerobic digester, chicken layers, pit storage < 1 month, pit storage > 1 month, others
u	product use	food (food), feed (feed), seed (seed), other use (other), substitution for byproducts (sby), substitution for aboveground crop residues (sag)
r	AG residue use	feed (feed), recycling to soils (rec), burning in the field (burn), other use (other)
b	conversion byproduct use	feed (feed), other use (other)

regions for each crop. Other removals ($P(x_t)^{\text{ds\_ag}}_{t,i,l,v,\text{other}}$) are assumed to be only in developing regions of major importance and is set in these regions to 10 % of total residue dry matter production (Smil, 1999). All residues not assigned to feed, food, burning or other removals are assumed to remain in the field ($P(x_t)^{\text{ds\_ag}}_{t,i,v,\text{rec}}$). Trade of residues between regions is not considered.

$$P(x_t)^{\text{prod\_ag}}_{t,i,v} = \sum_r P(x_t)^{\text{ds\_ag}}_{t,i,v,r} \tag{A4}$$

A2.2 Conversion byproducts

Conversion byproducts are generated in the manufacturing of harvested crops into processed food. Of major importance are press cakes from oil production, molasses and bagasses from sugar refinement and brans from cereal milling. While they are also consumed as food, used for bioenergy production or as fertilizer, their most important usage lies currently in livestock feeding. Until recently, they were also reported in FAOSTAT. As the feed baskets used by MAgPIE from Weindl et al. (2010) are not in line with the then unpublished but probably more accurate statistics of FAOSTAT (2011), we decided to use the latter estimates on production and use (for feed or other purposes). We distributed the byproducts between the different livestock production types proportional to their energy in the feed baskets from Weindl et al. (2010) to create livestock-specific feed baskets for conversion byproducts $r^{\text{fb\_by}}_{t,i,l,v}$.

In the model, the production of 8 different conversion byproducts $P(x_t)^{\text{prod\_by}}_{t,i,v}$ (brans, molasses and 6 types of oilcakes) is linked to the total domestic supply $\sum_u P(x_t)^{\text{ds}}_{t,i,v,u}$ of their belonging crop groups (Table A3.1) by a factor $r^{\text{by\_conv}}_{\text{i,v}}$ fixed to the ratio of conversion byproduct production to their belonging crop domestic supply in 1995 (FAOSTAT, 2011). If the demand for byproducts is higher than the production, byproducts from other regions can be imported or the model can also feed feedstock crops $P(x_t)^{\text{ds}}_{t,i,l,v,\text{sby}}$.

$$P(x_t)^{\text{prod\_by}}_{t,i,v} := \sum_u P(x_t)^{\text{ds}}_{t,i,v,u} \cdot r^{\text{by\_conv}}_{\text{i,v}} \tag{A5}$$

$$P(x_t)^{\text{ds\_by}}_{t,i,v,\text{feed}} = \sum_l (P(x_t)^{\text{prod}}_{t,i,l} \cdot r^{\text{fb\_by}}_{t,i,l,v} - P(x_t)^{\text{ds}}_{t,i,l,v,\text{sby}}) \tag{A6}$$

$$\sum_i P(x_t)^{\text{prod\_by}}_{t,i,v} = \sum_{i,b} P(x_t)^{\text{ds\_by}}_{t,i,v,b} \tag{A7}$$

A3 N_r flows

A3.1 Attributes of plant biomass, conversion byproducts and food

The parametrisation of the goods represented in the model is a core task in a material flow model. From the literature, we derived N_r content of dry matter of harvested organs r^{Nharvest}_v (Wirsenius, 2000; Fritsch, 2007; FAO, 2004; Roy et al., 2006), aboveground crop residues r^{Nag}_v (Wirsenius, 2000; Fritsch, 2007; FAO, 2004; Eggleston et al., 2006; Chan and Lim, 1980), belowground crop residues r^{Nbg}_v(Eggleston et al., 2006; Fritsch, 2007; Wirsenius, 2000; Khalid et al., 2000) and conversion byproducts r^{Nby}_v(Wirsenius, 2000; Roy et al., 2006) (Table A3.1). For the aggregation to MAgPIE crop groups, we weighted the parameters of each crop group with its global dry matter biomass in 1995. In the case of missing values for a specific FAO crop, we adopted the parametrisation of a selected representative crop of its crop group (e.g. we assign the value of wheat, being the representative crop of *temperate cereals*, to the FAO item *mixed grain*). The N_r in crop and residue production and its subsequent use is thus

Table A2. Parameters, descriptions and units (all units per year). The name of the equivalent parameter in Eggleston et al. (2006) is indicated in brackets.

Parameter	Description	Unit
Area		
$X^{\text{area}}_{t,j,v,w}$	Cropland area under cultivation	Mha
$\text{P}(x_t)^{\text{landconv}}_{t,j}$	Land conversion	Mha
Production		
$\text{P}(x_t)^{\text{prod}}_{t,i,k}$	Crop production	TgDM
$\text{N}(x_t)^{\text{prod}}_{t,i,k}$		TgN_r
$\text{P}(x_t)^{\text{prod\_ag}}_{t,i,v}$	AG residue production	TgDM
$\text{N}(x_t)^{\text{prod\_ag}}_{t,i,v}$		TgN_r
$\text{P}(x_t)^{\text{prod\_bg}}_{t,i,v}$	BG residue production	TgDM
$\text{N}(x_t)^{\text{prod\_bg}}_{t,i,v}$		TgN_r
$\text{P}(x_t)^{\text{prod\_by}}_{t,i,v}$	Conversion byproduct production	TgDM
$\text{N}(x_t)^{\text{prod\_by}}_{t,i,v}$		TgN_r
Domestic supply and its use		
$\text{P}(x_t)^{\text{ds}}_{t,i,v,u}$	Crop use	TgDM
$\text{N}(x_t)^{\text{ds}}_{t,i,v,u}$		TgN_r
$\text{P}(x_t)^{\text{ds\_ag}}_{t,i,v,r}$	AG residues use	TgDM
$\text{N}(x_t)^{\text{ds\_ag}}_{t,i,v,r}$		TgN_r
$\text{P}(x_t)^{\text{ds\_by}}_{t,i,v,b}$	Conversion byproduct use	TgDM
$\text{N}(x_t)^{\text{ds\_by}}_{t,i,v,b}$		TgN_r
$\text{N}(x_t)^{\text{fs}}_{t,i,k}$	Food supply	TgN_r
$r^{\text{int}}_{t,i,k}$	Intake share of food supply	$\frac{\text{TgN}_\text{r}}{\text{TgDM}}$
$\text{N}(x_t)^{\text{int}}_{t,i,k}$	Intake	TgN_r
P^{tb}_t	Trade balance reduction	1

obtained as follows:

$$\text{N}(x_t)^{\text{prod}}_{t,i,v} := \text{P}(x_t)^{\text{prod}}_{t,i,v} \cdot r^{\text{Nharvest}}_v \tag{A8}$$

$$\text{N}(x_t)^{\text{prod\_ag}}_{t,i,v} := \text{P}(x_t)^{\text{prod\_ag}}_{t,i,v} \cdot r^{\text{Nag}}_v \tag{A9}$$

$$\text{N}(x_t)^{\text{prod\_bg}}_{t,i,v} := \text{P}(x_t)^{\text{prod\_bg}}_{t,i,v} \cdot r^{\text{Nbg}}_v \tag{A10}$$

$$\text{N}(x_t)^{\text{ds}}_{t,i,v,u} := \text{P}(x_t)^{\text{ds}}_{t,i,v,u} \cdot r^{\text{Nharvest}}_v \tag{A11}$$

$$\text{N}(x_t)^{\text{ds\_ag}}_{t,i,v,r} := \text{P}(x_t)^{\text{ds\_ag}}_{t,i,v,r} \cdot r^{\text{Nag}}_v \tag{A12}$$

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A3.2 Manure management

Feed N_r is assigned to three feeding systems (f): pasture grazing (grazp), cropland grazing (grazc) and animal houses (house). All N_r from pasture was assigned to grazp. N_r in feedstock crops and conversion byproducts is assumed to be eaten in confinement houses. Crop residues in developed regions are fully assigned to house, while in developing regions we assume that 25 % of the N_r in residues are consumed directly on croplands during stubble grazing ($r^{\text{grazC}}_{t,i}$).

$$\text{N}(x_t)^{\text{feed}}_{t,i,l,\text{grazp}} := r^{\text{fb\_past}}_{t,i,l} \cdot \text{P}(x_t)^{\text{prod}}_{t,i,l} \cdot r^{\text{Npast}} \tag{A13}$$

$$\text{N}(x_t)^{\text{feed}}_{t,i,l,\text{grazc}} := \sum_v r^{\text{fb\_ag}}_{t,i,l,v} \cdot \text{P}(x_t)^{\text{prod}}_{t,i,l} \cdot r^{\text{Nag}}_v \cdot r^{\text{grazC}}_{t,i} \tag{A14}$$

$$\begin{aligned}\text{N}(x_t)^{\text{feed}}_{t,i,l,\text{house}} := & \sum_v \Big(r^{\text{fb\_by}}_{t,i,l,v} \cdot \text{P}(x_t)^{\text{prod}}_{t,i,l} \cdot r^{\text{Nby}}_v \\ & + r^{\text{Nharvest}}_v \cdot (r^{\text{fb\_conc}}_{t,i,l,v} \cdot \text{P}(x_t)^{\text{prod}}_{t,i,l} \\ & + \text{P}(x_t)^{\text{ds}}_{t,i,l,v,\text{sby}} + \text{P}(x_t)^{\text{ds}}_{t,i,l,v,\text{sag}}) \\ & + r^{\text{fb\_ag}}_{t,i,l,v} \cdot \text{P}(x_t)^{\text{prod}}_{t,i,l} \cdot r^{\text{Nag}}_v \cdot (1 - r^{\text{grazC}}_{t,i}) \Big)\end{aligned} \tag{A15}$$

In a second step, we use a top-down approach to estimate regional livestock specific annual average N_r excretion rates, rooted in the Tier 2 methodology of Eggleston et al. (2006). From the feed in all feeding systems (f) we subtract the amount of N_r which is integrated into animal biomass

Table A2. Continued.

Parameter	Description	Unit
Crop growth functions, processing rates and biological fixation		
$r^{\text{cgf\_i}}_v$	AG residues intercept	$\frac{\text{TgDM}}{\text{Mha}}$
$r^{\text{cgf\_s}}_v$	AG residues slope	$\frac{\text{TgDM}}{\text{TgDM}}$
$r^{\text{cgf\_r}}_v$	AG to BG biomass ratio	$\frac{\text{TgDM}}{\text{TgDM}}$
$r^{\text{by\_conv}}_{\text{i,v}}$	Conversion byproducts generated per unit of crop production	$\frac{\text{TgDM}}{\text{TgDM}}$
r^{ndfa}_v	Plant N_r derived from atmospheric fixation	$\frac{\text{TgN}_\text{r}}{\text{TgN}_\text{r}}$
r^{Nfix}_v	Fixation of free-living bacteria	$\frac{\text{TgN}_\text{r}}{\text{TgMha}}$
Products		
r^{Nharvest}_v	N_r content of harvested crops	$\frac{\text{TgN}_\text{r}}{\text{TgDM}}$
r^{Nag}_v	N_r content of AG residues	$\frac{\text{TgN}_\text{r}}{\text{TgDM}}$
r^{Nbg}_v	N_r content of BG residues	$\frac{\text{TgN}_\text{r}}{\text{TgDM}}$
r^{Npast}	N_r content of grazed pasture	$\frac{\text{TgN}_\text{r}}{\text{TgDM}}$
r^{Nby}_v	N_r content of conversion byproducts	$\frac{\text{TgN}_\text{r}}{\text{TgDM}}$
r^{PR}_l	Protein content of livestock products	$\frac{\text{TgPr}}{\text{TgDM}}$
r^{NtoPR}_l	Protein to N_r content ratios	$\frac{\text{TgN}_\text{r}}{\text{TgPr}}$

Table A2. Continued.

Parameter	Description	Unit
Livestock		
$r^{\text{fb\_conc}}_{t,i,l,v}$	Feedstock crops in feed basket	$\frac{\text{TgDM}}{\text{TgDM}}$
$r^{\text{fb\_ag}}_{t,i,l,v}$	AG residues in feed basket	$\frac{\text{TgDM}}{\text{TgDM}}$
$r^{\text{fb\_past}}_{t,i,l}$	Grazed pasture in feed basket	$\frac{\text{TgDM}}{\text{TgDM}}$
$r^{\text{fb\_by}}_{t,i,l,v}$	Byproducts in feed basket	$\frac{\text{TgDM}}{\text{TgDM}}$
$r^{\text{grazC}}_{t,i}$	Fraction of feed residues consumed during stubble grazing	$\frac{\text{TgDM}}{\text{TgDM}}$
$\text{N}(x_t)^{\text{feed}}_{t,i,l,f}$	Feed N_r distributed to livestock types in feeding systems	$\frac{\text{TgN}_\text{r}}{\text{TgN}_\text{r}}$
r^{sl}_{l}	Ratio between marketable product and whole body weight	$\frac{\text{TgDM}}{\text{TgDM}}$
r^{Nl}_{l}	Whole body N_r content	$\frac{\text{TgN}_\text{r}}{\text{TgDM}}$
$\text{N}(x_t)^{\text{sl}}_{t,i,l}$	N_r in whole animal bodies	TgN_r
$r^{\text{fs}}_{t,i,l,f}$	Fraction of manure in feeding system (based on $\text{MS}_{(\text{T,S})}$)	$\frac{\text{TgN}_\text{r}}{\text{TgN}_\text{r}}$
$r^{\text{cs}}_{t,i,l,c}$	Fraction of manure managed in animal waste management systems (based on $\text{MS}_{(\text{T,S})}$)	$\frac{\text{TgN}_\text{r}}{\text{TgN}_\text{r}}$
$\text{N}(x_t)^{\text{ex}}_{t,i,l,f}$	N_r in excretion ($\text{Nex}_{(\text{T})}$)	TgN_r
$r^{\text{fuel}}_{t,i,l}$	Fraction of manure collected for fuel	$\frac{\text{TgN}_\text{r}}{\text{TgN}_\text{r}}$
$\text{N}(x_t)^{\text{closs}}_{t,i}$	Manure N_r lost in animal houses and waste management	TgN_r

$\text{N}(x_t)^{\text{sl}}_{t,i,l}$ and assume that the remaining N_r is excreted as manure. For meat products, we calculate the N_r in the whole animal body $\text{N}(x_t)^{\text{sl}}_{t,i,l}$ using livestock product to whole body ratios r^{sl}_l from Wirsenius (2000), and whole body N_r content r^{Nl}_l based on Poulsen and Kristensen (1998) (Table A5). For milk and eggs, we calculate $\text{N}(x_t)^{\text{sl}}_{t,i,l}$ by the N_r content in milk and eggs (Poulsen and Kristensen, 1998) (Table A5). $\text{N}(x_t)^{\text{sl}}_{t,i,l}$ is assigned to one of the three feeding systems by the parameter $r^{\text{fs}}_{t,i,l,f}$, which is based on Eggleston et al. (2006).

$$\text{N}(x_t)^{\text{sl}}_{t,i,l} := \text{P}(x_t)^{\text{prod}}_{t,i,l}\frac{r^{\text{Nl}}_l}{r^{\text{sl}}_l} \quad \text{(A16)}$$

$$\text{N}(x_t)^{\text{ex}}_{t,i,l,f} := \text{N}(x_t)^{\text{feed}}_{t,i,l,f} - r^{\text{fs}}_{t,i,l,f}\cdot\text{N}(x_t)^{\text{sl}}_{t,i,l} \quad \text{(A17)}$$

In a third step, the N_r excreted in animal houses is divided between 9 animal waste management systems (c) using the parameter $r^{\text{cs}}_{t,i,l,c}$. When available, we used the regional and livestock specific shares from Eggleston et al. (2006); for chicken, sheep, goats and other animals, we used the default parameters of IPCC (1996). The category *others* for chicken is assumed to be *poultry with litter*.

Not all the manure excreted in animal houses is recycled within the agricultural system, but large fractions are lost to volatilisation and leaching or is simply not brought out to the farmland. We use animal waste management system specific

Table A2. Continued.

Parameter	Description	Unit
Soil Budget		
$\text{N}(x_t)^{\text{withd}}_{t,i}$	Soil N_r withdrawals	TgN_r
$\text{N}(x_t)^{\text{inp}}_{t,i}$	Soil N_r inputs	TgN_r
$\text{N}(x_t)^{\text{loss}}_{t,i}$	Soil N_r losses	TgN_r
$r^{\text{SNUpE}}_{t,i}$	Cropland soil N_r uptake efficiency	$\frac{\text{TgN}_\text{r}}{\text{TgN}_\text{r}}$
$\text{N}(x_t)^{\text{dep}}_{t,i}$	Atmospheric deposition of N_r	TgN_r
$\text{N}(x_t)^{\text{volat}}_{t,i}$	Volatilisation of NO_x and NH_y	$\text{TgNO}_\text{x}\text{NH}_\text{y}$
$\text{N}^{\text{som}}_{t,i}$	N_r release by soil organic matter loss (F_{SOM})	TgN_r
$r^{\text{som}}_{t,j}$	N_r release by soil organic matter loss	$\frac{\text{TgN}_\text{r}}{\text{Mha}}$
$\text{N}(x_t)^{\text{fert}}_{t,i}$	Inorganic N_r fertilizer (F_{SN})	TgN_r
$\text{N}(x_t)^{\text{res}}_{t,i}$	N_r in recycled AG and BG residues (F_{CR})	TgN_r
$\text{N}(x_t)^{\text{FixFree}}_{t,i}$	N_r fixed by free-living microorganisms (F_{CR})	TgN_r
$\text{N}(x_t)^{\text{m}}_{t,i}$	N_r in manure excreted in animal houses and applied to agricultural soils (F_{AM})	TgN_r
$r^{\text{msplit}}_{t,i}$	Fraction of manure in animal houses applied to cropland soils	$\frac{\text{TgN}_\text{r}}{\text{TgN}_\text{r}}$
$\text{N}(x_t)^{\text{m\_cs}}_{t,i}$	N_r in manure applied or excreted on cropland soils	TgN_r
$\text{N}(x_t)^{\text{m\_ps}}_{t,i}$	N_r in manure applied or excreted on pasture soils	TgN_r
Emissions		
$r^{\text{gas\_fert}}$	Fraction of industrial fertilizer N_r that volatises as NO_x and NH_y ($\text{Frac}_{\text{GasF}}$)	$\frac{\text{TgNO}_\text{x}\text{NH}_\text{y}}{\text{TgN}_\text{r}}$
$r^{\text{gas\_awms}}_{l,c}$	Fraction of manure N_r that volatises in waste management facilities as NO_x and NH_y ($\text{Frac}_{\text{GasMS}}$)	$\frac{\text{TgNO}_\text{x}\text{NH}_\text{y}}{\text{TgN}_\text{r}}$
$r^{\text{loss\_awms}}_{l,c}$	Fraction of manure N_r that is lost in waste management ($\text{Frac}_{\text{LossMS}}$)	$\frac{\text{TgNO}_\text{x}\text{NH}_\text{y}}{\text{TgN}_\text{r}}$

Table A2. Continued.

Parameter	Description	Unit
$r^{\text{gas\_m}}$	Fraction of manure N_r that volatises during application as NO_x and NH_y ($\text{Frac}_{\text{GasM}}$)	$\frac{\text{TgNO}_x\text{NH}_y}{\text{TgN}_r}$
r^{leach}	Fraction of N_r that leaches to water bodies ($\text{Frac}_{\text{Leach-H}}$)	$\frac{\text{TgN}_r}{\text{TgN}_r}$
r_v^{CF}	Combustion factor for on-field residue burning (C_f)	$\frac{\text{TgN}_r}{\text{TgN}_r}$
r^{dir}	Direct emission factor for N inputs to managed soils (EF_1)	$\frac{\text{TgN}_2\text{O-N}}{\text{TgN}_r}$
$r^{\text{dir\_rice}}$	Direct emission factor for N inputs to flooded rice fields ($\text{EF}_{1\text{fr}}$)	$\frac{\text{TgN}_2\text{O-N}}{\text{TgN}_r}$
$r_c^{\text{dir\_house}}$	Direct emission factor for manure excreted in animal houses ($\text{EF}_{3(S)}$)	$\frac{\text{TgN}_2\text{O-N}}{\text{TgN}_r}$
$r_l^{\text{dir\_graz}}$	Direct emissions from manure excreted on pasture, range and paddock ($\text{EF}_{3\text{PRP}}$)	$\frac{\text{TgN}_2\text{O-N}}{\text{TgN}_r}$
$r^{\text{indir\_gas}}$	N_2O emission factor for volatised N_r (EF_{iv})	$\frac{\text{TgN}_2\text{O-N}}{\text{TgNO}_x\text{NH}_y}$
$r^{\text{indir\_leach}}$	N_2O emission factor for leached N_r (EF_{v})	$\frac{\text{TgN}_2\text{O-N}}{\text{TgN}_r}$
$N_2O(x_t)_{t,i}^{\text{fert}}$	N_2O from industrial fertilizer	$\text{TgN}_2\text{O}-\text{N}$
$N_2O(x_t)_{t,i}^{\text{res}}$	N_2O from crop residues	$\text{TgN}_2\text{O}-\text{N}$
$N_2O(x_t)_{t,i}^{\text{m}}$	N_2O from animal manure applied to croplands	$\text{TgN}_2\text{O}-\text{N}$
$N_2O(x_t)_{t,i}^{\text{past}}$	N_2O from pasture range and paddock	$\text{TgN}_2\text{O}-\text{N}$
$N_2O(x_t)_{t,i}^{\text{house}}$	N_2O from animal waste management systems	$\text{TgN}_2\text{O}-\text{N}$
$N_2O(x_t)_{t,i}^{\text{som}}$	N_2O from soil organic matter loss	$\text{TgN}_2\text{O}-\text{N}$

shares of the total amount of managed manure $r_{l,c}^{\text{loss\_awms}}$ not being recycled, including a fraction $r_{l,c}^{\text{gas\_awms}}$ that is lost in the form of volatilisation in the form of NO_x and NH_y. Because default parameters for $r_{l,c}^{\text{gas\_awms}}$ and $r_{l,c}^{\text{loss\_awms}}$ are not available for all animal waste management systems, we made the following assumptions: For pit storage < 1 month of swine manure, we used the lower value of the proposed range (0.15), and the upper value (0.3) for pit storage > 1 month. If no estimates are available, drylots and solid storage received the same emission factor, as was done in the old methodology (IPCC, 1996). Based on Marchaim (1992), we assumed that losses for manure managed in *anaerobic digesters* are negligible. In the absence of default parameters for $r_{t,i,l,c}^{\text{cs}}$ for chicken, sheep, goats and other animals, we used the default parameters of Eggleston et al. (2006). *Others*

Table A3. Estimates of crop growth functions: AG residues intercept ($r_v^{\text{cgf\_i}}$), slope ($r_v^{\text{cgf\_s}}$) and AG to BG biomass ratio ($r_v^{\text{cgf\_r}}$) (for sources see text).

Crop type (kcr)	$r_v^{\text{cgf\_i}}$	$r_v^{\text{cgf\_s}}$	$r_v^{\text{cgf\_r}}$
Temperate cereals	0.58	1.36	0.24
Tropical cereals	0.61	1.03	0.22
Maize	0.79	1.06	0.22
Rice	2.46	0.95	0.16
Soybeans	1.35	0.93	0.19
Rapeseed	0	1.86	0.22
Groudnut	1.54	1.07	0.19
Sunflower	0	1.86	0.22
Oilpalm	0	1.86	0.24
Pulses	0.79	0.89	0.19
Potatoes	1.06	0.10	0.20
Tropical roots	0	0.85	0.20
Sugar cane	0	0.67	0.07
Sugar beet	0	0.54	0.20
Others	0	0.39	0.22
Fodder	0.26	0.28	0.45
Fibres	0	1.48	0.13

Table A4. N_r contents of harvested crops (r_v^{Nharvest}), aboveground crop residues (r_v^{Nag}), belowground crop residues (r_v^{Nbg}) and conversion byproducts (r_v^{Nby}) for the MAgPIE crop types. All N_r contents are in % of dry matter biomass. Collected and aggregated from Wirsenius (2000), Fritsch (2007), Eggleston et al. (2006), FAO (2004), Roy et al. (2006), Chan and Lim (1980) and Khalid et al. (2000).

Crop type (v)	r_v^{Nharvest}	r_v^{Nag}	r_v^{Nbg}	r_v^{Nby}
Temperate cereals	2.17	0.74	0.98	2.93
Maize	1.60	0.88	0.70	
Tropical cereals	1.63	0.70	0.60	
Rice	1.28	0.70	0.90	
Soybeans	5.12	0.80	0.80	7.90
Rapeseed	3.68	0.81	0.81	6.43
Groudnut	2.99	2.24	0.80	7.28
Sunflower	2.16	0.80	0.80	5.92
Oilpalm	0.57	0.52	0.53	6.43
Pulses	4.21	1.05	0.80	
Potatoes	1.44	1.33	1.40	
Tropical roots	0.53	0.86	1.40	
Sugar cane	0.24	0.80	0.80	1.36
Sugar beet	0.56	1.76	1.40	
Others	2.85	0.81	0.70	5.72
Fodder	2.01	1.91	1.41	
Fibres	2.39	0.93	0.70	
Pasture	1.60			
Pasture	r^{Npast}			
Past	1.60			

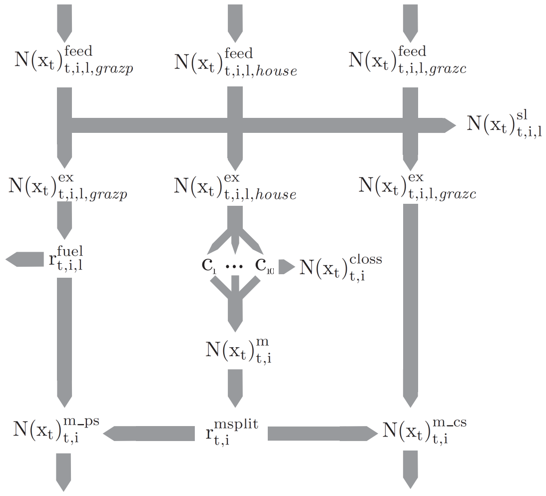

Fig. A1. Modelling N_r flows in the livestock sector.

Table A5. Estimates of whole body N_r content (r_l^{Nl}) in % of dry matter, and estimates of the ratio between marketable product and whole body weight (r_l^{sl}).

	r_l^{Nl}	r_l^{sl}
Ruminant livestock	6.3[a]	0.66[c]
Non-ruminant livestock	6.0[a]	0.81[c]
Poultry	7.1[a]	0.76[c]
Eggs	5.6[a]	1
Milk	4.6[b]	1

[a]Based on cows, market pigs, chicken and chicken eggs in Poulsen and Kristensen (1998).
[b]Based on milk with 3.5 % proteins in line with Smil (2002).
[c]Based on medium quality cows, swine and broilers from Wirsenius (2000).

is assumed to be *deep bedding* for pigs, cattle and others. All remaining gaps in the loss factors are filled with the values for cattle of the respective animal waste management system.

While all remaining manure in animal houses is fully applied to cropland soils in developing regions, we assume that in NAM and EUR only a fraction $r^{msplit}_{t,i}$ of 87 % and 66 % is returned on cropland soils (Liu et al., 2010b), while the rest is applied to pasture soils. Furthermore, in developing regions, a certain share of manure excreted on pasture is dedicated for household fuel and does not return to pasture soils (Eggleston et al., 2006). Because the N_r in fuel is leaving the agricultural sector, it is not further considered in this study, while the N_r from pasture grazing is assumed to be returned to pasture soils.

Losses of N_r in animal houses and waste handling ($N(x_t)^{closs}_{t,i}$), recycled manure ($N(x_t)^{m}_{t,i}$) and manure arriving on cropland soils ($N(x_t)^{m\_cs}_{t,i}$) and pasture soils ($N(x_t)^{m\_ps}_{t,i}$) are calculated as follows:

$$N(x_t)^{closs}_{t,i} := \sum_c N(x_t)^{ex}_{t,i,l,\text{house}} \cdot r^{cs}_{t,i,l,c} \cdot r^{loss\_awms}_{l,c} \tag{A18}$$

$$N(x_t)^{m}_{t,i} := \sum_c N(x_t)^{ex}_{t,i,l,\text{house}} \cdot r^{cs}_{t,i,l,c} \cdot (1 - r^{loss\_awms}_{l,c}) \tag{A19}$$

$$N(x_t)^{m\_cs}_{t,i} := N(x_t)^{m}_{t,i} \cdot r^{msplit}_{t,i} + \sum_l N(x_t)^{ex}_{t,i,l,\text{grazc}} \tag{A20}$$

$$N(x_t)^{m\_ps}_{t,i} := N(x_t)^{m}_{t,i} \cdot (1 - r^{msplit}_{t,i}) + \sum_l N(x_t)^{ex}_{t,i,l,\text{grazp}} \cdot (1 - r^{fuel}_{t,i,l}) \tag{A21}$$

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A3.3 Cropland N_r inputs

Inorganic fertilizer is the only N_r flow appearing in international statistics. We aggregate the values of IFADATA (2011) for all N_r fertilizer products to the 10 MAgPIE regions to determine $N(x_t)^{fert}_{t,i}$ in 1995. For the scenario analysis, inorganic fertilizer consumption is determined endogenously as described in Sect. A3.4.

The amount of crop residues left in the field is estimated as described in Sect. A2 as the remainder of the produced residues which are not used for feed, construction, fuel or burned in the field. While the nutrients of these residues are fully returned to cropland soils, the largest part of the N_r in the crop residues burned in the field (r^{CF}_v) is combusted; only a fraction of 10 % for temperate cereal residues and 20 % for all other residues (Eggleston et al., 2006) remains uncombusted and returns to cropland soils.

$$N(x_t)^{res}_{t,i} := \sum_v \Big(N(x_t)^{prod\_bg}_{t,i,v} + N(x_t)^{ds\_ag}_{t,i,v,\text{rec}} + N(x_t)^{ds\_ag}_{t,i,v,\text{burn}} \cdot (1 - r^{CF}_v) \Big) \tag{A22}$$

A major part of the N_r lost from field in the form of NO_x and NH_y as well as other N_r compounds from the combustion of fossil fuels are later on deposited from the atmosphere on cropland area. Based on spatial datasets for atmospheric deposition rates (Dentener, 2006) and cropland area (Klein Goldewijk et al., 2011a), we derive the regional atmospheric deposition on croplands $N(x_t)^{dep}_{t=1,i}$. As a large part of volatilised N_r will be deposited close to the emission source, the largest part of cropland atmospheric deposition probably stems from agricultural NO_x and NH_y. For the future we therefore assume that the deposition rates grow with the same growth rate as the agricultural NO_x and NH_y emissions $N(x_t)^{volat}_{t,i}$ (see Eq. (A38) in Sect. A3.5).

$$N(x_t)^{dep}_{t,i} := \frac{N(x_t)^{volat}_{t,i}}{N(x_t)^{volat}_{t=1,i}} \cdot N(x_t)^{dep}_{t=1,i} \tag{A23}$$

Table A6. Estimates of N_r fixation rates per area (r_v^{Nfix}) or as percentage of plant N_r (r_v^{ndfa}), based on Herridge et al. (2008) and aggregated to MAgPIE crop types.

Crop type	r_v^{Nfix} $\frac{TgN_r}{Mha}$	r_v^{ndfa} $\frac{TgN_r}{TgN_r}$
Temperate Cereals	0.005	–
Maize	0.005	–
Tropical Cereals	0.005	–
Rice	0.033	–
Soybeans	–	0.5[a], 0.6 [b], 0.8 [c], 0.68[d]
Rapeseed	0.005	–
Groudnut	–	0.5[a], 0.6 [b], 0.8 [c], 0.68[d]
Sunflower	0.005	–
Oilpalm	0.005	–
Pulses	–	0.53
Potatoes	0.005	–
Tropical roots	0.005	–
Sugar Cane	–	0.2[b], 0.1[d]
Sugar Beet	0.005	–
Others	0.005	–
Fodder	0.004	0.31
Fibres	0.005	–

[a]For the region CPA
[b]For the region LAM
[c]For the region NAM
[d]For all other regions

While plants are unable to fix nitrogen from N_2 in the atmosphere, some microorganisms are able to do this. These microorganisms either live free in soils, or in symbiosis with certain crops or cover crops. The symbiosis is typical mainly for leguminous crops (beans, groundnuts, soybean, pulses, chickpeas, alfalfa), which possess special root nodules in which the microorganisms live. Also, sugar cane can fix N_r in symbiosis with endophytic bacteria. In the case of rice paddies, free-living cyanobacteria and cyanobacteria living in symbiosis with the water-fern Azolla can also fix substantial amounts of N_r. While N_r fixation by leguminous plants has been well investigated, estimates for N_r fixation by sugar cane and free-living bacteria is much more uncertain or even speculative.

For legumes and sugar cane, where N_r fixation is the direct product of a symbiosis of the microorganisms with the crop, we assumed that fixation rates are proportional to the N_r in the plant biomass. The percentage of fixation-derived N_r is taken from Herridge et al. (2008). In the case of soybeans, groundnuts and sugarcane, fixation rates vary between regions to account for differences in management practices like fertilization or inoculation.

For legumes and sugar cane, where N_r fixation is the direct product of a symbiosis of the microorganisms with the crop, we assumed that fixation rates are proportional to the N_r in the plant biomass. The percentage of fixation-derived N_r is taken from Herridge et al. (2008). In the case of soybeans, groundnuts and sugarcane, fixation rates vary between regions to account for differences in management practices like fertilization or inoculation. N_r fixation by free-living bacteria in cropland soils and rice paddies does not necessarily depend on the biomass production of the harvested crop, so we used fixation rates per area r_v^{Nfix}. In the case of the MAgPIE crop types fodder and pulses, which contain crop species with different rates of N_r fixation, a weighted mean is calculated based on the relative share of biomass production in 1995 for r_v^{ndfa} or on the relative share of harvested area in 1995 for r_v^{Nfix} (Table A6). Our model does not cover that the fixation rates might change in the future due to the change of management practices. Improved inoculation of root nodules could increase fixation rates, while fertilization of legumes could reduce the biological fixation.

$$N(x_t)_{t,i}^{FixFree} := \sum_{j\in I_i, v, w} X_{t,j,v,w}^{area} \cdot r_v^{Nfix}) \quad (A24)$$

A certain share of the N_r in a plant is already incorporated in the seed. The amount of seed required for production $P(x_t)_{t,i,v,seed}^{ds}$ is estimated crop and region specific using seed shares from FAOSTAT (2011).

$$N(x_t)_{t,i,v,seed}^{ds} := P(x_t)_{t,i,v,seed}^{ds} \cdot r_v^{Nharvest} \quad (A25)$$

When pastureland or natural vegetation is transformed to cropland, soil organic matter (SOM) is lost. This also releases N_r for agricultural production. Total N_r release by SOM loss $N_{t,i}^{som}$ is estimated by multiplying the land conversion $P(x_t)_{t,j}^{landconv}$ in each grid cell with the yearly N_r losses per ha $r_{t,j}^{som}$.

$$N_{t,i}^{som} = \sum_{j\in I_i} \left(P(x_t)_{t,j}^{landconv} \cdot r_{t,j}^{som} \right) \quad (A26)$$

Land conversion $P(x_t)_{t,j}^{landconv}$ is calculated as the increase of $X_{t,j,v,w}^{area}$ into area that has previously not been used as cropland. As pastureland and natural vegetation have a similar level of SOM (Eggleston et al., 2006), we can calculate the N_r inputs from SOM loss $N_{t,i}^{som}$ on the basis of land conversion for cropland, independent of whether the expansion occurs into natural vegetation or pastureland. After the conversion of cropland, we assume that cropland management releases 20 to 52 % of the original soil carbon, depending on the climatic region (Eggleston et al., 2006), plus the full litter carbon stock of the cell. Soil and litter carbon were estimated using the natural vegetation carbon pools of LPJmL. N_r losses per hectare converted cropland $r_{t,j}^{som}$ are then estimated on a cellular basis from the carbon losses, using a fixed C : N ratio of 15 for the conversion of forest or grassland to cropland. In reality, the soil carbon is released over a period of 20 yr until the carbon stock arrives in the new equilibrium (Eggleston et al., 2006). For simplification, we assume that all N_r

is released in the timestep of conversion (10 yr). To derive the yearly N_r release per ha $r^{som}_{t,j}$, we divide N_r losses per hectare by 10 and assume no delayed release in the subsequent decade.

As MAgPIE is calibrated to the cropland area in 1995, no land conversion occurs in this timestep. To estimate $P(x_t)^{landconv}_{t=1,j}$, we use the HYDE database with a 5 arcminutes resolution (Klein Goldewijk et al., 2011a). We define land conversion as the sum of (positive) cropland expansion in each geographic grid cell into land which was not used as cropland since the year 1900. In the case that cropland area first shrinks and then increases again, it is assumed that the same cropland area is taken into management that was abandoned before, so that no new SOM loss takes place. The high spatial resolution of Klein Goldewijk et al. (2011a) is of importance, because with higher aggregation (e.g. country-level estimates by FAOSTAT, 2011) expansion and contraction of cropland area within the same aggregation unit cancel out and land conversion is underestimated. The results for the historical estimates can be found in Table A7. The estimates for 1990–2000 are too high. The HYDE estimates are based on an older release of FAOSTAT data, while more recent FAOSTAT data corrected cropland expansion significantly downwards, reaching even a negative net expansion for the period 1990–2000 (Klein Goldewijk , 2011b). To estimate the contribution of N_r released by SOM loss to the N_r budget in 1995, we therefore only used the period 1980–1990.

A3.4 Losses and inorganic fertilizer

We calculate regional soil nitrogen uptake efficiency (SNUpE) $r^{SNUpE}_{t=1,i}$ in 1995 by dividing total soil withdrawals $N(x_t)^{withd}_{t=1,i}$ by total soil inputs $N(x_t)^{inp}_{t=1,i}$.

$$r^{SNUpE}_{t=1,i} = \frac{N(x_t)^{withd}_{t=1,i}}{N(x_t)^{inp}_{t=1,i}} \quad \text{(A27)}$$

The soil inputs include inorganic fertilizer, manure, N_r released from soil organic matter loss, recycled crop residues, atmospheric deposition and N_r fixation by free-living bacteria and algae. N_r in seed as well as N_r fixation by legumes and sugarcane are not counted as soil inputs, as they reach the plant not via the soil. Soil withdrawals are calculated by subtracting from the N_r in plant biomass (harvested organ, above- and belowground biomass) the amount of N_r that is not taken up from the soil and therefore not subject to losses prior to uptake. The latter includes again seed N_r as well as the N_r fixed from the atmosphere by legumes and sugarcane.

$$\begin{aligned} N(x_t)^{withd}_{t,i} := \sum_v \Big(& (1 - r^{ndfa}_v) \cdot (N(x_t)^{prod}_{t,i,v} \\ & + N(x_t)^{prod\_ag}_{t,i,v} + N(x_t)^{prod\_bg}_{t,i,v}) \\ & - N(x_t)^{ds}_{t,i,v,seed} \Big) \end{aligned} \quad \text{(A28)}$$

$$\begin{aligned} N(x_t)^{inp}_{t,i} := & N(x_t)^{fert}_{t,i} + N(x_t)^{res}_{t,i} + N(x_t)^{m\_cs}_{t,i} \\ & + N^{som}_{t,i} + N(x_t)^{dep}_{t,i} + N(x_t)^{FixFree}_{t,i} \end{aligned} \quad \text{(A29)}$$

The loss of N_r from cropland soils $N(x_t)^{loss}_{t,i}$ is defined as the surplus of soil inputs over soil withdrawals.

$$N(x_t)^{loss}_{t,i} := N(x_t)^{inp}_{t,i} - \sum_v N(x_t)^{withd}_{t,i} \quad \text{(A30)}$$

For the year 1995, we use historical data on regional fertilizer consumption based on (IFADATA, 2011) to estimate $r^{SNUpE}_{t=1,i}$. In the following timesteps, $r^{SNUpE}_{t,i}$ is fixed on an exogenous level (see Sect. A4), while the model balances out the regional budget by endogenously determining the amount of required inorganic fertilizer $N(x_t)^{fert}_{t,i}$.

$$N(x_t)^{inp}_{t,i} \geq \frac{N(x_t)^{withd}_{t,i}}{r^{SNUpE}_{t,i}} \quad \text{(A31)}$$

A3.5 Emissions

We distinguish into emissions from inorganic fertilizer ($N_2O(x_t)^{fert}_{t,i}$), crop residues ($N_2O(x_t)^{res}_{t,i}$), animal manure excreted or applied on cropland ($N_2O(x_t)^{m}_{t,i}$), manure excreted on pasture range and paddock ($N_2O(x_t)^{past}_{t,i}$), animal waste management ($N_2O(x_t)^{house}_{t,i}$) and soil organic matter loss ($N_2O(x_t)^{som}_{t,i}$). Each emission category has direct N_2O emissions plus eventually indirect emissions from volatilisation and leaching.

Direct N_2O emissions from soils are calculated as a fraction r^{dir} of the inputs from manure, fertilizer, crop residues and soil organic matter loss. According to Eggleston et al. (2006), paddy rice has lower direct emissions (r^{dir_rice} instead of r^{dir}) from fertilization with inorganic fertilizers. As our methodology is unable to estimate the amount of inorganic fertilizer which is used specifically for rice production, we use EF_{1FR} for all N_r inputs of rice. The direct emission factor for emissions from N_r excreted during pasture range and paddock $r^{dir\_graz}_l$ diverges between different animal types. For our livestock categories "ruminant meat" and "ruminant milk", containing animals of different types, we used weighted averages according to net excretion rates in 1995.

N_2O emissions from volatilisation occur when inorganic fertilizer or manure is applied to fields. The fraction volatilising in the form of NO_x or NH_y is different between the excretion or application of manure (r^{gas_m}), the application of inorganic fertilizer (r^{gas_fert}) and the management of animal

Table A7. Land conversion due to cropland expansion and release of N_r from subsequent soil organic matter (SOM) loss. For sources see text.

		Net expansion[a]	Land conversion[b]	SOM loss from land conversion			
		10^6 ha	10^6 ha	Tg C	Tg N_r	$\frac{kgN_r}{ha}$	$\frac{kgN_r}{ha \cdot yr}$ [c]
World	1960–1970	53	77	2574	172	2226	111
World	1970–1980	30	66	2464	164	2486	124
World	1980–1990	69	103	3754	250	2432	122
– AFR	1980–1990	13	17	529	35	2137	107
– CPA	1980–1990	33	25	848	57	2237	112
– EUR	1980–1990	−3	3	115	8	2885	144
– FSU	1980–1990	−2	9	542	36	4019	201
– LAM	1980–1990	8	12	489	33	2708	135
– MEA	1980–1990	5	4	48	3	738	37
– NAM	1980–1990	−1	13	614	41	3045	152
– PAO	1980–1990	4	5	108	7	1342	67
– PAS	1980–1990	10	10	359	24	2441	122
– SAS	1980–1990	2	5	103	7	1505	75
World	1990–2000[d]	22	325	12 370	825	2535	127

[a] Net expansion counts the aggregated change in regional or global cropland, and thus the difference of expansion and contraction.
[b] Land conversion sums up the expansion of each geographic grid cell into land which was not used as cropland since the year 1900. Contracting cropland is not substracted.
[c] Assuming that the soil organic matter is lost over 20 yr.
[d] Estimates for 1990–2000 are too high and should not be used (see text).

waste($r_{l,c}^{\mathrm{gas\_awms}}$). A fraction $r^{\mathrm{indir\_gas}}$ of these NO_x and NH_y gases transforms later on into N_2O.

Leaching is relevant for inorganic fertilizer application, residue management as well as the excretion or application of animal manure to agricultural soils. We assume, that a fraction r^{leach} of the applied N_r leaches into water bodies. According to Eggleston et al. (2006), r^{leach} is only relevant on croplands where runoff exceeds water holding capacity or where irrigation is employed, while for this model we made the simplification that leaching occurs everywhere. This assumption is also used in IPCC (1996). Of all N_r leaching into water bodies, a fraction $r^{\mathrm{indir\_leach}}$ is assumed to transform later on into N_2O.

The following equations sum up the calculations according to the emission sources:

$$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{fert}} := \mathrm{N}(x_t)_{t,i}^{\mathrm{fert}} \cdot (r^{\mathrm{dir}} + r^{\mathrm{gas\_fert}} \cdot r^{\mathrm{indir\_gas}} + r^{\mathrm{leach}} \cdot r^{\mathrm{indir\_leach}}) \tag{A32}$$

$$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{res}} := \mathrm{N}(x_t)_{t,i}^{\mathrm{res}} \cdot (r^{\mathrm{dir}} + r^{\mathrm{leach}} \cdot r^{\mathrm{indir\_leach}}) \tag{A33}$$

$$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{m}} := \mathrm{N}(x_t)_{t,i}^{\mathrm{m}} \cdot (r^{\mathrm{dir}} + r^{\mathrm{gas\_m}} \cdot r^{\mathrm{indir\_gas}} + r^{\mathrm{leach}} \cdot r^{\mathrm{indir\_leach}}) \tag{A34}$$

$$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{past}} := \sum_{l} \Big(\mathrm{N}(x_t)_{t,i,l,\mathrm{grazp}}^{\mathrm{ex}} + \mathrm{N}(x_t)_{t,i,l,\mathrm{grazc}}^{\mathrm{ex}} \big) \cdot \big(r_l^{\mathrm{dir\_graz}} + r^{\mathrm{gas\_m}} \cdot r^{\mathrm{indir\_gas}} + r^{\mathrm{leach}} \cdot r^{\mathrm{indir\_leach}} \Big) \tag{A35}$$

$$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{house}} := \sum_{l,c} \Big(\mathrm{N}(x_t)_{t,i,l,\mathrm{house}}^{\mathrm{ex}} \cdot r_{t,i,l,c}^{\mathrm{cs}} \cdot (r_{l,c}^{\mathrm{gas\_awms}} \cdot r^{\mathrm{indir\_gas}} + r_c^{\mathrm{dir\_house}}) \Big) \tag{A36}$$

$$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{som}} := \mathrm{N}_{t,i}^{\mathrm{som}} \cdot (r^{\mathrm{dir}} + r^{\mathrm{leach}} \cdot r^{\mathrm{indir\_leach}}) \, . \tag{A37}$$

The NO_x and NH_y volatilisation on cropland area $\mathrm{N}(x_t)_{t,i}^{\mathrm{volat}}$, which is required for the calculation of atmospheric deposition in Eq. A23, is calculated as follows:

$$\mathrm{N}(x_t)_{t,i}^{\mathrm{volat}} := \mathrm{N}(x_t)_{t,i}^{\mathrm{fert}} \cdot r^{\mathrm{gas\_fert}} + (\mathrm{N}(x_t)_{t,i}^{\mathrm{m}} + \mathrm{N}(x_t)_{t,i,l,\mathrm{grazp}}^{\mathrm{ex}} + \mathrm{N}(x_t)_{t,i,l,\mathrm{grazc}}^{\mathrm{ex}}) \cdot r^{\mathrm{gas\_m}} + \sum_{l,c} (\mathrm{N}(x_t)_{t,i,l,\mathrm{house}}^{\mathrm{ex}} \cdot r_{t,i,l,c}^{\mathrm{cs}} \cdot r_{l,c}^{\mathrm{gas\_awms}}) \, . \tag{A38}$$

The 2006 guidelines differ from the widely used 1996 guidelines (IPCC, 1996) most importantly in two aspects. Firstly, the N_r fixed by legumes and other N_r-fixing plants is not considered to have significant N_2O emissions. Only their comparably N_r-rich crop residues contribute to the N_2O emissions if they are left on the field. Secondly, the emission factor from leached N_r (EF_5, in our case $r^{\mathrm{indir\_leach}}$) was lowered considerably from 2.5 % to 0.75 %.

To estimate the sensitivity of our results in regard to the uncertainty of the emission parameters, we carried out a Monte Carlo analysis with the software @Risk. We used a log-logistic probability density function (PDF) for the emission parameters r^{dir}, $r_c^{\mathrm{dir\_house}}$, $r_l^{\mathrm{dir\_graz}}$, $r^{\mathrm{indir\_gas}}$, $r^{\mathrm{indir\_leach}}$, r^{leach}, $r^{\mathrm{gas\_fert}}$, $r^{\mathrm{gas\_m}}$, and $r_{l,c}^{\mathrm{gas\_awms}}$. We chose this PDF, because it is non-negative, and because the median and the quantiles can be defined freely. We used the default value as mean and the uncertainty range from Eggleston et al. (2006) as 2.5 % and 97.5 % confidence intervals. We assumed that emission factors are non-correlated between each other. As the uncertainty range of the emission parameters in Eggleston et al. (2006) were estimated for country inventories, it is questionable whether they should be regarded as correlated between countries or not. We decided to regard the parameters as not correlated between regions, but as fully correlated for all countries within a region. As a consequence, regional uncertainties partly cancel out, and our global emission estimates have a lower relative uncertainty range. To simplify our calculation, we did not differentiate between waste management systems for animals kept in confinement, and simply assumed an error range of −50 % to +100 % for the aggregated mean of $r_c^{\text{dir\_house}}$ and $r_{l,c}^{\text{gas\_awms}}$.

We express the resulting uncertainty range for the emissions as a 90 % confidence interval, as the uncertainty distribution becomes very flat for higher significance levels.

A3.6 Food supply and intake

N_r in food supply is not equal to the N_r in harvested crops and slaughtered animals assigned for food, because the food products are processed. For food supply of crop products $N(x_t)^{\text{fs}}_{t,i,v}$, we therefore subtracted the N_r in conversion byproducts from the N_r in harvest assigned for food. Also, in the case of livestock products, the amount of N_r in the final products is not equal to the amount of N_r in the slaughtered animals, as only certain parts of the slaughtered animal are marketed, while the fifth quarter (often including head, feet, intestines and blood) is not used for food. Therefore, we calculated protein content per food product r_l^{PR} based on FAOSTAT (2011) and multiplied them with product specific protein–N_r ratios r_l^{NtoPR} from Sosulski and Imafidon (1990) and Heidelbaugh et al. (1975) to estimate the amount of N_r in livestock food supply ($N(x_t)^{\text{fs}}_{t,i,l}$).

Finally, the food supply is significantly higher than actual intake $N(x_t)^{\text{int}}_{t,i,k}$ because of significant waste rates on household level or in catering. We used regional intake to supply shares $r^{\text{int}}_{t,i,k}$ from Wirsenius (2000). As these shares will change with rising income, we estimated actual intake only for the year 1995.

$$N(x_t)^{\text{fs}}_{t,i,v} := N(x_t)^{\text{ds}}_{t,i,v,\text{food}} - N(x_t)^{\text{prod\_by}}_{t,i,v} \quad \text{(A39)}$$

$$N(x_t)^{\text{fs}}_{t,i,l} := N(x_t)^{\text{prod}}_{t,i,l} \cdot r_l^{\text{PR}} \cdot r_l^{\text{NtoPR}} \quad \text{(A40)}$$

$$N(x_t)^{\text{int}}_{t,i,k} := N(x_t)^{\text{fs}}_{t,i,k} \cdot r^{\text{int}}_{t,i,k} \quad \text{(A41)}$$

A4 Scenarios

For future projections, we created scenarios based on the SRES storylines (Nakicenovic et al., 2000). Quantitative interpretations of these storylines have been done by various integrated assessment models, whereof marker scenarios were selected. We use downscaled projections of population and per capita income of these marker scenarios as main drivers of the MAgPIE model (CIESIN, 2002a,b).

Bodirsky et al. (2012) create food demand scenarios for plant and livestock products based on the SRES population and GDP marker scenarios. To account for materialistic and non-materialistic lifestyles, they use different regressional forms for the A and B scenarios. In the A scenarios, they apply a log–log regression with a positive continuous time-trend for total caloric intake, and a multiple linear regression model for the livestock demand share. For the sustainable B scenarios, they use a log–log regression with positive declining time trend for total caloric intake, and an inverted u-shape regression model for livestock demand. In the latter, the share of animal products is increasing for low and medium incomes, but decreases for high incomes. The functional forms of the B scenarios tend to result in lower demand than the regression in the A scenarios. Yet, all four regressions are consistent with past observations (Table A8). The calculations are carried out on country level and are subsequently aggregated to the 10 MAgPIE regions. The scenarios are calibrated to meet the food demand in 1995 (FAOSTAT, 2011), the initial year of the MAgPIE model. Afterwards, they converge linearly towards the regression values throughout the 21st century to account for a globalisation of diets.

In all scenarios, the global food demand more than doubles from 1990 to 2070 (Fig. A2), while towards the end of the 21st century, the globalised scenarios A1 and B1 have a slightly declining food demand. Demand for livestock products (Fig. A3) is rising disproportionally strong, yet declines in all but the A2 scenario towards the end of the century.

The food demand projections are based on population and income growth of the SRES scenarios, starting in 1990. As can be seen in figure A2 and A3, the historical data of food demand is met more or less precisely depending on the scenario. Global food calorie demand diverges in 2005 by 98 PJ (+0.4 %) (B1) to 452 PJ (1.7 %) (B1), while meat demand diverges by −244 PJ (−5.2 %) (A2) to +60 PJ (1.2 %) (B2). The largest differences can be observed in the estimates for meat demand in CPA, where the A2 scenario diverges by −422 PJ (−31.5 %) while the B2 scenario almost matches the observed data with 15 PJ (+1.1 %). Large parts of these variations in estimates are determined by the uncertainty of the original SRES projections for population and GDP.

A parameter which is subject to large uncertainty is the development of future trade liberalisation policies. For 1995, we fix the share of domestic demand settled by imported products at their actual level in 1995. For the subsequent timesteps, we assume that an increasing share can be traded according to comparative advantages in production costs. The share of products traded according to historical trade patterns decreases in turn by 10 % per decade in the two globalised scenarios A1 and B1. These scenarios are equivalent to the policy scenario of Schmitz et al. (2012), extended

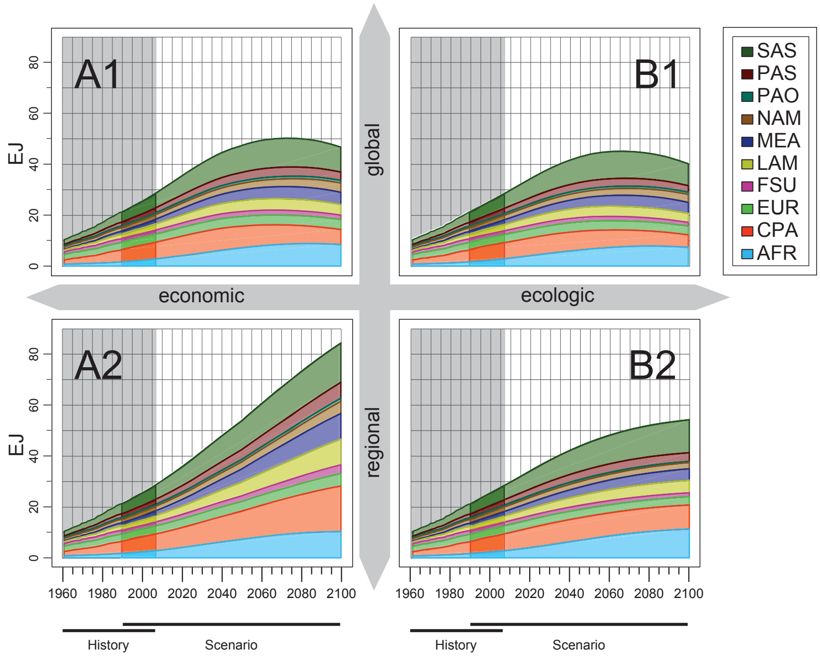

Fig. A2. Total food energy demand in the 10 MAgPIE world regions. History and future developments for the four SRES scenarios (Bodirsky et al., 2012).

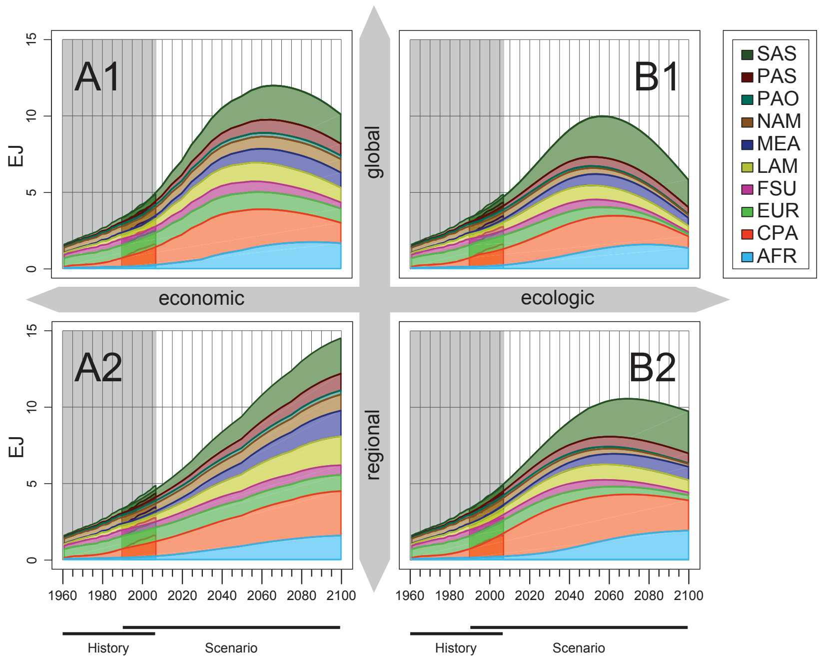

Fig. A3. Demand for energy from livestock products in the 10 MAgPIE world regions. History and future developments for the four SRES scenarios (Bodirsky et al., 2012).

Table A8. Regression models for total calories C_T in kcal and the share of livestock calories in total demand C_S, depending on income I in 2005 US Dollar in market exchange rate.

SRES	Model	Formulae	Parameter	Slope	r^2	p-value	F-statistics
A	Calories	$C_T = a \cdot (I)^b$	$a = \exp(2.825 + 2.131 \times 10^{-3} \cdot \text{year})$, $b = 0.162 - 3.124 \times 10^{-5} \cdot \text{year}$	0.658	0.65	<0.001 (***)	11060
	Livestock share	$C_S = \exp(k + l \cdot \ln(I) + m \cdot \text{year} + n \cdot \ln(I) \cdot \text{year})$	$k = -36.733, l = 4.497$, $m = 0.016, n = -0.002$	0.705	0.63	<0.001 (***)	9913
B	Calories	$C_T = a \cdot (I)^b$	$a = 933.89 + \frac{387.47 \cdot (\text{year}-1960)}{\text{year}-1960+9.77}$, $b = 0.0894 + \frac{0.008445 \cdot (\text{year}-1960)}{\text{year}-1960-0.75569}$	0.678	0.64	<0.001 (***)	10551
	Livestock share	$C_S = p \cdot \sqrt{I} \cdot \exp(-q \cdot I)$	$p = 0.00932 - 3.087 \times 10^{-6} \cdot \text{year}$, $q = -2.654 \times 10^{-4} + 1.420 \times 10^{-7}$	0.706	0.62	<0.001 (***)	9685

to 2095. For the regionalised scenarios, we assume a slower rate of market integration with a reduction of only 2.5 % per decade.

The efficiency of nutrient uptake on croplands is a parameter which has strong impact on the results of the model. While we estimate this parameter for the base year 1995, its development into the future is rather uncertain. Policies like the nitrate directive in Europe seemed to have a large impact in the past (Oenema et al., 2011), so the environmental awareness seems to be a key driver of N_r efficiency. To differentiate the economically orientated from the environmentally orientated scenarios, we adjust the cropland nutrient uptake efficiency $r_{t,i}^{\text{SNUpE}}$ for future scenarios. The starting points for $r_{t=1,i}^{\text{SNUpE}}$ are calculated endogenously in the model, and converge linearly over n timesteps to their scenario values $r_{n,i}^{\text{SNUpE}}$ (Table 1).

$$r_{t,i}^{\text{SNUpE}} := (1 - \frac{t}{n}) \cdot r_{t=1,i}^{\text{SNUpE}} + \frac{t}{n} \cdot r_{n,i}^{\text{SNUpE}} \tag{A42}$$

We chose to have high efficiency values in the B scenario due to high awareness for local environmental damages. The most efficient agricultural systems currently absorb around 70 % of applied N (Smil, 1999), and Vuuren et al. (2011) estimate that "in practice, recovery rates of 60–70 % seem to be the maximum achievable". So we adopted this value for the environmentally oriented B scenarios. In the A1 scenario, we assumed that $r_{t,i}^{\text{SNUpE}}$ increases due to widespread use of efficient technologies (e.g. precision farming), which saves costs but also resources. Yet, no improvements beyond cost efficiency are made, thus $r_{t,i}^{\text{SNUpE}}$ stays behind the B scenarios towards the end of the century. Finally, the A2 scenario stagnates slightly above the current mean, and only improves towards the end of the century.

A further scenario parameter is the development of livestock production systems. Feed baskets and livestock productivity diverge significantly in different world regions, with some systems being more industrialised and consuming mainly feedstock crops, others being pastoral or mixed systems. While the development of the livestock system is highly uncertain, a trend towards industrialised systems can be observed (Delgado, 1999). For future scenarios, we converge the feed baskets and livestock productivity linearly towards the European livestock system, a system with rather low share of pastoral and traditional systems and a high share of industrialised livestock production. We assume a fast convergence in the globalised systems A1 and B1, while the regional scenarios keep more of their current regional feed mixes (Table 1). To implement this into the model, we converged the parameters $r_{t,i,l,v}^{\text{fb\_conc}}$, $r_{t,i,l}^{\text{fb\_past}}$, $r_{t,i,l,v}^{\text{fb\_ag}}$, $r_{t,i,l,v}^{\text{fb\_by}}$ and $r_{t,i,l,f}^{\text{fs}}$ similar to Eq. (A42) to the European values in 1995. To account for an increasing modernization of the agricultural sector, the same type of convergence is applied to $r_{t,i}^{\text{msplit}}$ and $r_{t,i,l}^{\text{fuel}}$ and the fractions of byproducts and crop residues burned or used for other purposes.

Even more uncertain is the development of the animal waste management. Even for the present, little information exists on the differences of animal waste management around the world, and there is no clear pattern as to which of the systems is dominating with increasing modernization. Similarly, we assumed that manure management for housed animals is changing over time. For the economically orientated scenarios and the B1 scenario, we assumed that bioenergy plants using anaerobic digesters increase in importance, while the B scenarios also have an increasing share of manure being directly brought back on fields as daily spread. The convergence towards these systems is higher in globalised scenarios, while the current regional animal waste management mix partly prevails in the A2 and B2 scenarios. In the model, we implemented the convergence for the parameter $r_{t,i,l,c}^{\text{cs}}$ similar to Eq. (A42).

Supplementary material related to this article is available online at: http://www.biogeosciences.net/9/4169/2012/bg-9-4169-2012-supplement.zip.

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Chapter IV: Livestock production and the water challenge of future food supply: implications of agricultural management and dietary choices

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Contents

Livestock production and the water challenge of future food supply: implications of agricultural management and dietary choices

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Abstract. Human activities use more than half of accessible freshwater, above all for agriculture. Most approaches for reconciling water conservation with feeding a growing population focus on the cropping sector. However, livestock production is pivotal to agricultural resource use, due to its low resource-use efficiency upstream in the food supply chain. Using a global modelling approach, we estimate that current feed production accounts for 38% of global crop water consumption and that water consumption related to grazing represents 29% of the total agricultural water footprint (9990 km^3yr^{-1}). Our analysis shows that changes in diets and livestock productivity have substantial implications for future consumption of agricultural blue water (19-36% increase compared to current levels) and green water (26-69% increase), but they can, at best, slow down trends of rising agricultural water requirements for decades to come. However, moderate productivity reductions in highly intensive livestock systems are possible without aggravating water scarcity. Productivity gains in developing regions decrease total water consumption, but lead to expansion of irrigated agriculture, due to the shift from grassland/green water to cropland/ blue water resources. Our analysis emphasises that the potential of demand and supply-side measures to reduce water scarcity depends on indirect dynamics mediated through changing trade flows, economic competitiveness of irrigation, and repercussions on investments into research and development. While the magnitude of the livestock water footprint gives cause for concern, neither dietary choices nor changes in livestock productivity will solve the water challenge of future food supply, unless accompanied by dedicated water protection policies.

Keywords: livestock; productivity; dietary changes; consumptive water use; water scarcity; water resources

1. Introduction

Water is essential to all life on Earth and may be regarded as the "bloodstream of the biosphere" (Rockström et al., 1999). Around the world, more than half of fresh and accessible runoff water is used by human enterprises (Postel et al., 1996); by far the largest share of this use (~70%) is attributable to agriculture (Rost et al., 2008). In contrast to the recommended annual basic water requirements of 18 m^3 per capita for drinking, hygiene, sanitation, and food preparation (Gleick, 1996), an annual 1300 m^3 of water per capita is needed to produce a balanced diet (Rockström et al., 2007).

At a closer look, the composition of diets - especially the share of animal-based products – substantially influences the water requirements of food production (Jalava et al., 2014; Liu and Savenije, 2008; Rockström et al., 2007). Depending on the climatic conditions and production methods, 1 to 5 m^3 of water are needed to produce 1 kg of grain, while 5 to 20 times more water is required to produce 1 kg of livestock products (Chapagain and Hoekstra, 2003). As in the case of humans, water for animals is primarily needed to eat rather than to drink. Water requirements for livestock drinking and servicing are very small and represent only 0.6% of global freshwater use (Herrero et al., 2009; Peden et al., 2007; Steinfeld et al., 2006). Therefore, how much and what kind of feed is used to produce one unit of livestock products entails important implications for livestock related water consumption.

There is substantial heterogeneity with regard to total feed efficiency (product output per feed input) and feed basket composition across different livestock production systems and levels of intensification (Herrero et al., 2013). As a consequence, shifts in production systems and improved livestock productivity are increasingly considered as an important lever to enhance resource efficiency of the livestock sector and confine the environmental burden of agriculture as a whole (Bouwman et al., 2013; Cohn et al., 2014; Havlík et al., 2014; Herrero et al., 2013; Steinfeld and Gerber, 2010; Valin et al., 2013; Weindl et al., 2015; Wirsenius et al., 2010). Changes in livestock production systems and related feed baskets do not only affect total livestock water productivity (product output per water input) (Herrero et al., 2009; Peden et al., 2007; Thornton and Herrero, 2010), but also the type of water resources involved in the production of animal feed, either green water from naturally infiltrated rainwater or blue irrigation water withdrawn from rivers, lakes and aquifers (Hoekstra and Chapagain, 2007). Besides affecting the relative importance of blue and green water consumption, production systems and feed basket composition also determine the share of water consumed on cropland and rangeland (de Fraiture et al., 2007).

While understanding livestock systems is crucial to assess the water challenge of feeding a growing and increasingly wealthy world population with changing dietary preferences towards animal-based products (Popp et al., 2017; Rosegrant et al., 2009; Valin et al., 2014), several authors state that interrelations between livestock and water have widely been disregarded by both water and livestock research communities to date (Bossio, 2009; Cook et al., 2009; Herrero et al., 2009; Peden et al., 2007; Thornton and Herrero, 2010). Recently, dietary changes have climbed up the scientific agenda as an option to reduce the water requirements of food production (Gerten et al., 2011; Jalava et al., 2014; Liu and Savenije, 2008; Mekonnen and Hoekstra, 2012; Vanham et al., 2013). However, recommendations to cut down on consumption of livestock products in order to protect water resources are often based on static inventories of livestock related water consumption and resulting virtual water content (*VWC*) of livestock products. Moreover, these studies do not account for secondary effects like shifting trade flows, altered incentives to invest in land and water productivity (*WP*) and reallocation of water resources between food and feed crops. To our knowledge, no study addresses implications of changes in feed efficiencies and livestock production systems on global water resources.

In the analysis presented here, we aim to take a step forward in unravelling the effects of the livestock sector on water use and obtaining a broader picture of options to meet the water challenge of future food supply. We estimate current and future levels of agricultural green and blue water consumption attributable to livestock production and assess potentials of dietary changes and shifts in livestock production systems to reduce agricultural water requirements and attenuate water scarcity. For this purpose, we apply the global land and water use model MAgPIE (Model of Agricultural Production and its Impact on the Environment) (Bodirsky et al., 2014; Popp et al., 2014; Stevanović et al., 2016) where the livestock sector is represented as a highly interconnected part of agricultural activities. Links between livestock and crop production are established through regional and product-specific feed baskets that evolve with the level of intensification, through trade-induced shifts in production, investments in research and development (R&D) and competition for land and water resources between food and animal feed production.

2. Methods and data

2.1. Modelling framework

MAgPIE is a global economic land and water use model that operates in a recursive dynamic mode and incorporates spatially explicit information on biophysical constraints into an economic decision making process (Lotze-Campen et al., 2008). It is thus well suited to analyse interactions between socio-economic processes, the natural resources required in agricultural production and related environmental impacts. By minimizing a nonlinear global cost function for each time step, the model fulfils demand for food, feed and materials for 10 world regions (Table 1).

Table 1. Socio-economic regions in MAgPIE.

Acronyms	MAgPIE regions
AFR	Sub-Sahara Africa
CPA	Centrally Planned Asia (incl. China)
EUR	Europe (incl. Turkey)
FSU	Former Soviet Union
LAM	Latin America
MEA	Middle East and North Africa
NAM	North America
PAO	Pacific OECD (Australia, Japan and New Zealand)
PAS	Pacific Asia
SAS	South Asia (incl. India)

Spatially explicit data on biophysical constraints are provided by the Lund-Potsdam-Jena managed land model (LPJmL) (Bondeau et al., 2007; Müller and Robertson, 2014; Rost et al., 2008) on 0.5 degree resolution and include pasture productivity, crop yields under both rainfed and irrigated conditions, related irrigation water demand per crop, water availability for irrigation as well as blue and green water use consumption per crop. LPJmL is a process-based model which simulates natural vegetation at the biome level by nine plant functional types (Sitch et al., 2003) and agricultural production by 12 crop functional types (Bondeau et al., 2007; Lapola et al., 2009) as well as associated terrestrial carbon and water cycles. Although LPJmL allows for transient simulations of agriculture and natural vegetation under climate change (Müller and Robertson, 2014; Rosenzweig et al., 2013), we deliberately exclude climate change impacts and instead focus on socio-economic dynamics that drive green and blue water consumption along the food supply chain.

In response to involved production costs (SI appendix, section A.1) and biophysical constraints, MAgPIE optimizes geographically explicit land use patterns and simulates major dynamics of the agricultural sector like R&D investments (Dietrich et al., 2012, 2014) and associated increases in both crop yields and biomass removal through grazing on pastures, land use change (including deforestation, abandonment of agricultural land and conversion between cropland and pastures), interregional trade flows, and irrigation (see section 2.3). Land types explicitly represented in MAgPIE comprise cropland, pasture, forest, urban areas, and other land (e.g. non-forest natural vegetation, abandoned agricultural land, and desert). Natural vegetation or pasture can only be converted to cropland if the land is at least marginally suitable for rainfed crop production with regard to climate, topography and soil type according to the Global Agro-Ecological Assessment (GAEZ) methodology on land suitability (Fischer et al., 2002; Krause et al., 2013; van Velthuizen et al., 2007). Parts of the forests are excluded from conversion into agricultural land if designated for wood production or located in protected areas (FAO, 2010). More information on the model version underlying this study can be found in the SI appendix.

2.2. Livestock sector

Livestock products (ruminant meat, whole-milk, pork, poultry meat and eggs) are supplied by five animal food systems (beef cattle, dairy cattle, pigs, broilers and laying hens) that further account for different animal functions (reproducers, producers and replacement animals). The parameterization of the livestock sector in the initial year 1995 is consistent with FAO statistics (FAOSTAT, 2013) regarding livestock production, livestock productivity and concentrate feed use. Following the methodology of Wirsenius (2000), feed conversion F_C (total feed input per product output in dry matter) and feed baskets F_B (demand for different feed types per product output in dry matter) are derived by compiling system-specific feed energy balances (see SI appendix for more details). For the establishment of these balances, we apply feed energy requirements per output, as estimated by Wirsenius (2000) for each animal function and animal food system. These estimates are based on standardized bio-energetic equations and include the minimum energy requirements for maintenance, growth, lactation, reproduction and other basic biological functions of the animals. Moreover, they comprise a general allowance for basic activity and temperature effects.

Establishing feed energy balances also requires information on feed energy supply. Feed use data from the CBS for food crops and food industry by-products are supplemented by production data on forage crops (FAOSTAT, 2013) and by estimates on feed use covering other categories like crop residues, food waste and grazed biomass (Bodirsky et al., 2012; Eggleston et al., 2006; Krausmann et al., 2008; Lal, 2005; Wirsenius, 2000). Understanding dynamics of F_C and F_B composition over time is crucial to assess future pathways of the livestock sector. To facilitate projections, we create regression models with livestock productivity P (annual production per animal [ton/animal/year]) as predictor, which permit the construction of productivity dependent feed baskets (SI appendix, section A.3).

2.3. *Agricultural water use*

Both rainfed and irrigated cropping activities rely on the availability of water resources. Crop water consumption is provided by LPJmL and consists of a productive (i.e. transpiration) and an unproductive (i.e. interception and evaporation) part, originating from liquid surface water (i.e. rivers, lakes and aquifers) in the case of blue water consumption B or directly from local precipitation in the case of green water consumption G. Water consumption on irrigated cropland also comprises green components (G_{irr}) which are quantified by LPJmL based on the fraction between irrigation and precipitation water (Rost et al., 2008). Rainfed agriculture exclusively involves green water consumption (G_{rf}). While we use total evapotranspiration (ET, productive plus unproductive consumption) on cropland to estimate crop water consumption, biomass generated on permanent pastures only partially enters the livestock sector as feed. Therefore, we differentiate between green water evapotranspired on total pasture area (G_{past_area}) and ET related to the fraction of biomass actually grazed by animals (G_{past_feed}). The difference can be interpreted as sustaining other ecosystem services (G_{past_ecosys}) on grasslands. Increases in biomass removal on existing pastures are assumed to increase G_{past_feed} at the expense of G_{past_ecosys}, reflecting an intensification of pasture management. In LPJmL, both irrigation water applied to the field and precipitation are further separated into interception, transpiration, soil evaporation, soil moisture and runoff (Rost et al., 2008), thus including non-consumptive components. For detailed information on the general soil water balance, river routing and water consumption, see Schaphoff et al. (2013) and Rost et al. (2008).

Green water productivity (gWP), defined as green water consumed per harvested biomass (m^3/tDM), evolves non-linearly with increasing crop yields due a vapour shift from non-productive evaporation (E) to productive transpiration (T) (J. I. Stewart et al., 1975; Rockström, 2003; Rockström et al., 2007). While T increases linearly with crop growth, E declines with increased soil surface shading from a denser crop canopy, with both processes taking place at different speeds. To account for corresponding changes in ET, we employ a non-linear relationship between yield and gWP, following equation 4.1 in Rockström (2003):

$$gWT = \frac{gWP_T}{(1 - e^{bY})}, \tag{1}$$

where gWP_T is the productive part of gWP (T flow, m^3/tDM), $b = -0.3$ is a constant, and Y is crop yield (tDM/ha). We use this empirical relationship, which is validated against a number of empirical field observations on grains in both tropical and temperate environments (Rockström et al., 2007), to estimate relative improvements of gWP compared to the initial parametrisation in 1995 due to simulated increases in crop yields over the simulation period.

Net irrigation water demand *(NIW)* is derived from the soil water deficit below optimal plant growth for simulated crop functional types by LPJmL (Rost et al., 2008) and corrected for losses from source to plant (Bonsch et al., 2015; Rohwer et al., 2007) to estimate gross irrigation water demand per crop (*GIW*) and resulting water withdrawals for irrigation (Wd_{irr}). There are several options to improve irrigation project efficiency (e_p=NIW/GIW) through increase in application efficiency, which describes losses when water is applied to the field and varies between surface, sprinkler and drip irrigation, and conveyance efficiency, accounting for losses during the transport from source to the field (e.g. via open canals or pipeline systems) (Rost et al., 2008). Moreover, irrigation water productivity can be enhanced by minimizing losses in across-field distribution, increasing the ratio of harvested plant biomass to total biomass production, and improving plant water use efficiency by breeding and better management of all inputs (Bonsch et al., 2015). Therefore, we assume that R&D investments improving crop yields simultaneously improve irrigation water productivity (Bonsch et al., 2014), thus leaving gross irrigation water demand per area constant. This is in line with findings that better agronomic practices and yield gains are crucial for augmenting water use efficiency (Kijne et al., 2004; Molden et al., 2010; Rosegrant et al., 2009). To test implications of this assumption, we conduct a sensitivity analysis where *GIW* linearly increase with crop yields.

Blue water availability in MAgPIE only accounts for renewable freshwater resources (*RFWR*), which are defined by total runoff as simulated by LPJmL during the growing season (Bonsch et al., 2014). Simulation units with water storage infrastructure (Biemans et al., 2011) contribute total annual runoff to basin water availability. Following an approach by Schewe et al. (2014), *RFWR* at basin level is distributed to simulation units by using discharge as weight on a monthly basis. Non-agricultural human water withdrawals Wd_{other} for industry, electricity and domestic use are obtained from WaterGAP (Alcamo et al., 2003; Flörke et al., 2013) and enter the model as exogenous pathways, thus reducing the de facto water availability for agriculture. Based on yield differences between rainfed and irrigated crops, crop-specific irrigation water demand *NIW*, the availability of blue water and presence of irrigation infrastructure, the model can endogenously decide to apply irrigation and expand the area equipped for irrigation at additional costs (Bonsch et al., 2014, 2015). Irrigation costs include investment costs for establishing new irrigation infrastructure, which are based on Worldbank data (Jones, 1995), and annual costs for operating irrigation systems (Bonsch et al., 2014).

We contextualize estimates of water consumption by two complementary water scarcity indicators to capture the environmental and agro-economic relevance of agricultural water use: the model internal water shadow price (*WSP*) for agro-economic and the water withdrawal-to-availability ratio (*WTA*) for biophysical evaluation of pressures on water resources, where *WTA* is defined as

$$WTA = \frac{Wd_{irr} + Wd_{other}}{RFWR}. \quad (2)$$

The *WSP* is calculated as the Lagrange multiplier of the water-balance constraints and indicates the value of an additional unit of irrigation water in the context of all constraints and costs that guide the economic decision process, thereby reflecting availability and suitability of natural resources for agriculture including geographically explicit limitations for rainfed agriculture, as well as the socio-economic setting (Biewald et al., 2014; Schmitz et al., 2013).

2.4. Scenarios

Socio-economic drivers are parametrized in line with the Shared Socioeconomic Pathways (SSPs) for climate change research (Kriegler et al., 2017; O'Neill et al., 2014; Popp et al., 2017). This study follows the narrative of SSP2, a "Middle of the Road" scenario. Average per capita food demand in 2050 amounts to 3174 kcal per day, with a contribution of 21% from animal-based calories (excluding fish). In order to assess demand- and supply-side potentials in the livestock sector to reduce agricultural water requirements, we construct eight scenarios (Table 2) along the dimensions of *dietary choices* and *livestock productivity* (annual production per animal).

Table 2. Overview of scenario framework.

Scenario		Description
Dietary choices	SSP2	Food demand trajectories according to the SSP2 narrative with an average per capita food demand of 3174 kcal per day and 21% animal-based products in dietary calories in 2050
	DEMI	Gradual change towards a demitarian Western diet with a share of animal-based products in dietary calories of no more than 15% in 2050
Livestock productivity	BASELINE	Livestock productivity trajectories according to the SSP2 narrative with medium pace in productivity increases and a slight catch-up of low productive systems
	DIVERGENCE	Continuation of historically observed very divergent productivity trends with little improvements in low productive systems
	CATCH-UP	SSP2 + further closure of current productivity gap by 45% for ruminant systems and by 60% for monogastric systems until 2050
	MODERATION	SSP2 + productivity reductions in highly productive systems to the level of 75% relative to the current productivity frontier defined by top-performing countries in 2010

In addition to the baseline diet scenario (SSP2), we consider an alternative development of dietary preferences (SI appendix, Fig. S7), which represents a gradual change of SSP2 diet projections to lower shares of animal-based calories in diets, with 15% as upper limit in 2050 for calories from livestock and fish. This scenario (DEMI) builds upon the concept of a "demitarian" Western diet in sustainability research (Bodirsky et al., 2014; Sutton and Ayyappan, 2013), with the share of animal-based calories being approximately half the currently observed level in OECD countries. In some developing regions, projected intake of livestock products under the SSP2 scenario does not reach these levels and is therefore unaffected by reductions.

The diet scenarios are combined with four alternative assumptions on future livestock productivity (see Fig. 1 for global and SI appendix, Fig. S8 for regional trends). The BASELINE scenario (livestock sector parametrisation according to SSP2 storyline) is characterized by a medium pace in productivity improvements, but low-productive regions catch up to a certain extent (Popp et al., 2017). The DIVERGENCE scenario represents the continuation of historically observed very divergent productivity developments with little improvements in some regions' low productive systems and is constructed by following the extrapolation of historical trends between 1970 and 2010, if these extrapolated trends are lower than SSP2 projections. In contrast to the DIVERGENCE scenario, where low livestock productivities are assumed to prevail, the ambitious CATCH-UP scenario prescribes a further closure of the current productivity gap, defined by top-performing countries in 2010, by 45% for ruminant systems and by 60% for monogastric systems until 2050. We assume a stronger intensification trend for non-ruminant systems, since the majority of future increases in poultry and pork production is expected to occur in industrial systems (Herrero et al., 2009; Steinfeld et al., 2006). The MODERATION scenario explores a variation of SSP2 livestock productivity trends at the opposite end of the range, the highly intensive systems. Until 2050, these systems are assumed to experience a reduction in livestock productivity to the level of 75% relative to the current productivity frontier defined by top-performing countries in 2010. The MODERATION scenario explores the relevance of further productivity improvements in intensive systems for resource use and the room to maneuver for measures to tackle other challenges related to livestock production that might impede productivity, such as improvements in animal welfare.

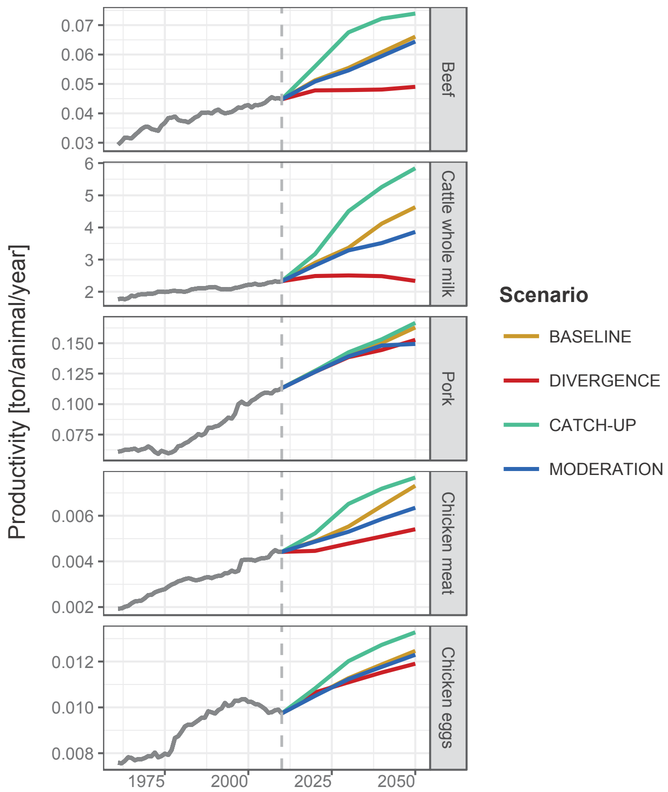

Fig. 1. Global past and future livestock productivity *P* (annual production per animal [ton fresh matter/animal/year]) for all livestock products. Historical developments (left of the vertical dashed line) according to FAOSTAT (2013) and future developments (right of the vertical dashed line) for the four productivity scenarios. Global aggregates are determined by regional productivity trends (see Fig. S8) and allocation of production between world regions.

3. Results

3.1. Contemporary water withdrawals and consumption

The pivotal role of green water resources for agricultural production is apparent in our results for the year 2010, estimating 6040 km^3yr^{-1} for green (G) and 1020 km^3yr^{-1} for blue (B) water consumed by crops, of which 2290 km^3yr^{-1} G and 370 km^3yr^{-1} B can be attributed to feed production on cropland (Table 3). Accordingly, the livestock sector is responsible for 38% of global crop water consumption. Considering also evapotranspiration on pastures, the prominence of green water for agriculture becomes even more distinct. Water consumption related to grazed biomass ($G_{past\_feed} = 2930\ km^3yr^{-1}$) represents 29% of the resulting

9990 km^3yr^{-1} water consumed by the entire agricultural sector ($G + B + G_{past\_feed}$). Water consumption attributable to livestock production constitutes 56% of this estimate of total agricultural water consumption, while 10% is related to B. Despite B coming secondary with respect to total agricultural water consumption, associated water withdrawals (Wd_{irr}) of 2610 km^3yr^{-1} represent 77% of all anthropogenic water withdrawals ($Wd_{irr} + Wd_{other} =$ 3390 km^3yr^{-1}), consequently being of primary importance with respect to human appropriation of freshwater resources. The resulting severe limitation of freshwater availability is a prevailing phenomenon in much of the populated regions of the world (Fig. 2).

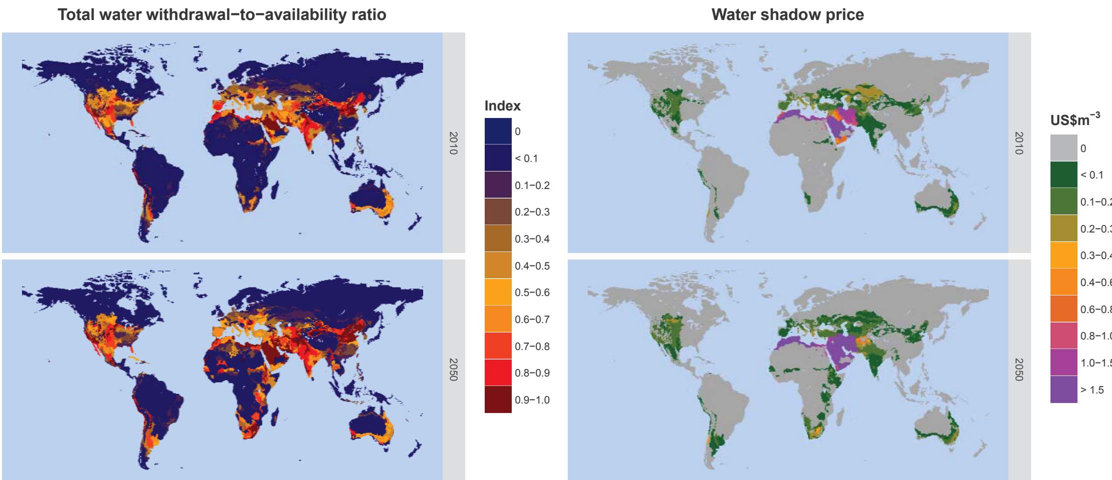

Fig. 2. Global distribution of the water withdrawal-to-availability ratio (*WTA* - left panel) and the water shadow price (*WSP* - right panel) for the SSP2 BASELINE scenario and the years 2010 and 2050. The *WTA* ratio is calculated as *WTA=Wd/RFWR*, where *Wd* represents water withdrawals from all sectors and RFWR denotes renewable freshwater resources. The WSP is calculated as the Lagrange multiplier of the water-balance constraints.

3.2. *Livestock futures and global water resources*

For the SSP2 BASELINE scenario, we estimate an increase in agricultural B by 310 km^3yr^{-1} (+30%) and G by 3400 km^3yr^{-1} (+56%) between 2010 and 2050 (Fig. 3, Table 3). Water consumption of feed crops (Fig. 4) accounts for 560 km^3yr^{-1} B (+51%) and 3980 km^3yr^{-1} G (+74%). Driven by the extension of irrigated cropping, additional 690 km^3yr^{-1} (+26%) blue water is withdrawn from *RFWR*. Due to more intensive pasture management, pasture area as well as related *ET* decline, while G connected to grazed biomass slightly increases by 150 km^3yr^{-1} (+5%). Global water resources are strongly affected by future demand- and supply-side changes of livestock production, where the type of resource use (green or blue water on cropland or pasture) is essentially influenced by assumptions on livestock productivity.

For BASELINE productivity trends, we estimate under different diet scenarios that 40-41% of livestock related water consumption in 2050 is attributable to grazed biomass, 7-8% to B and the remaining 51-52% to G related to cropland feed. Compared to 2010, this represents a shift from green water resources on grasslands to those on cropland. A further catch-up of less productive systems (CATCH-UP) strengthens this trend, with only 33-35% of livestock water consumption related to G_{past_feed} and 58-59% to G, a consequence of substantial pasture-to-cropland conversion processes. With respect to absolute values, CATCH-UP scenarios feature lowest values of livestock water consumption, together with highest values of water consumed by feed production (Fig. 4) and agricultural Wd_{irr}. (Fig. 3). High demand for feed crops results in the expansion of both rainfed and irrigated cropland and in higher water scarcity on arable land (e.g. South Asia and Sub-Saharan Africa) (see Fig. 5 for global and SI appendix, Fig. S15 for regional results).

On the contrary, a continuation of divergent productivity trajectories (DIVERGENCE scenarios) involves lowest crop water consumption, total cropland area as well as cropland prone to water stress, but at the expense of a rising contribution from pastures to *G*. This is partly facilitated by the exploitation of *ET* on newly converted pasture (+16% and +5% increase of G_{past_area} for SSP2 and DEMI diet scenarios), implying a loss of natural vegetation. For all other diet and productivity scenarios, Gpast_area decreases over time by 5-13% (Table 3). Productivity reductions in highly productive systems (MODERATION) have minor and ambiguous effects on type and magnitude of livestock related water consumption and water scarcity.

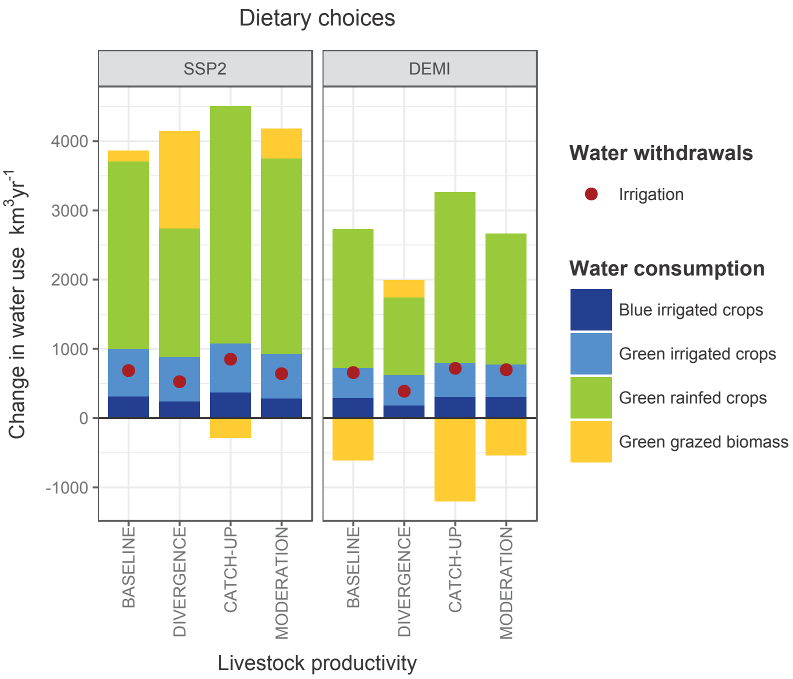

Fig. 3. Changes in global agricultural green (*G*) and blue (*B*) water consumption between 2010 and 2050 in km^3yr^{-1}. Red points indicate changes in global water withdrawals for irrigation (Wd_{irr}) between 2010 and 2050 in km^3yr^{-1}. Note that water consumption on irrigated cropland also comprises green components (G_{irr}).

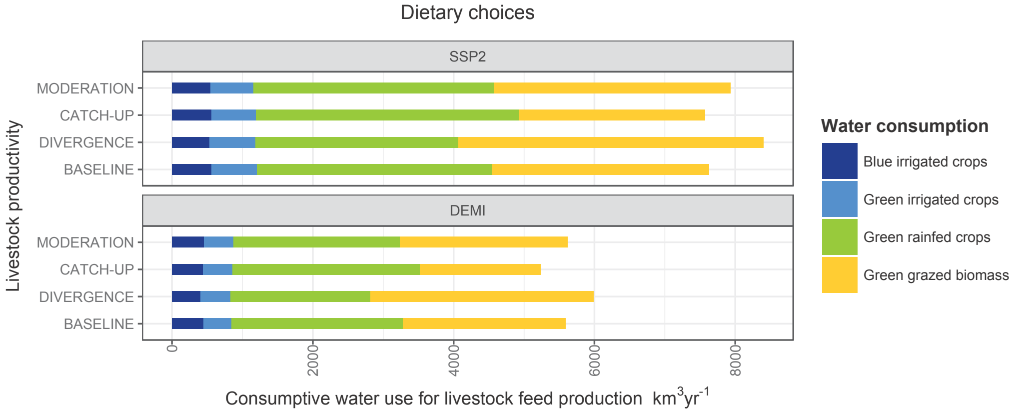

Fig. 4. Global agricultural green (G) and blue (B) water consumption in 2050 attributable to livestock feed production in km^3yr^{-1}. Vertical stacked lines indicate water consumption related to feed production in 2010 in km^3yr^{-1}. Note that water consumption on irrigated cropland also comprises green components (G_{irr}).

For all productivity scenarios, lower intake of livestock products (DEMI) entails a reduction of water consumption related to cropland feed and grazed biomass (Fig. 4). As a consequence, we also observe a general decline in total agricultural water consumption (both G and B on cropland and pasture) and similar patterns with respect to productivity scenarios, with the exception of B for the MODERATION scenarios. Reductions in demand for livestock products also attenuate cropland requirements and levels of water stress (Fig. 5). While G_{past_feed} and G are quite sensitive to dietary changes (25-35% and 10-12% reduction compared to SSP2 diets), B and Wd_{irr} are less responsive. In contrast to G_{past_feed} being basically determined by demand for grazed biomass and G, which beside spatial relocation of crop production is principally driven by cropping area and yield, B is additionally influenced by water availability and economic competitiveness of irrigation activities and establishment of irrigation infrastructure compared to cropland expansion and R&D investments.

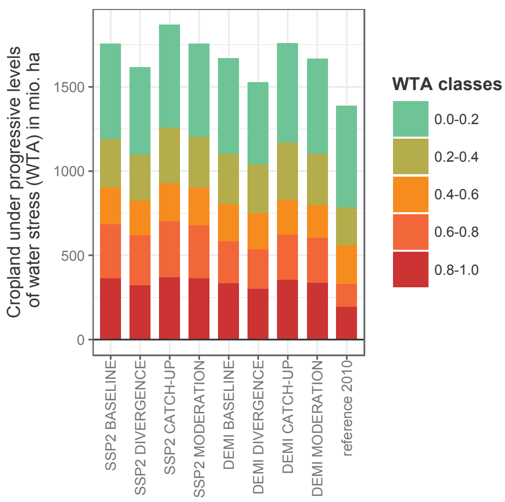

Fig. 5. Global cropland under progressive levels of water stress in million ha, derived by aggregating cropland area of concordant WTA classes from simulation units to global values. The length of each bar represents total global cropland. The last bar indicates values for the reference year 2010. Scenario results are given for 2050.

Table 3. Global green (G) and blue (B) water consumption attributable to total agriculture and the livestock sector in 2010 in km^3yr^{-1} and percentage changes between 2010 and 2050 for all scenarios. G on cropland is differentiated according to rainfed (G_{rf}) and irrigated cropland (G_{irr}). On pastures, G is differentiated between evapotranspiration on total pasture area (G_{past_area}) and G attributable to grazed biomass (G_{past_feed}), the residuum being interpreted as sustaining ecosystem services (G_{past_ecosys}).

		SSP2 (2050)				DEMI (2050)			
	2010	BASELINE	DIVERGENCE	CATCH-UP	MODERATION	BASELINE	DIVERGENCE	CATCH-UP	MODERATION
Total agriculture									
B	1020	+30%	+24%	+36%	+28%	+28%	+19%	+30%	+30%
G_{irr}	790	+89%	+82%	+90%	+82%	+56%	+56%	+62%	+59%
G_{rf}	5250	+52%	+35%	+65%	+54%	+38%	+21%	+47%	+36%
G	6040	+56%	+41%	+69%	+57%	+41%	+26%	+49%	+39%
$G + B$	7070	+52%	+39%	+64%	+53%	+39%	+25%	+46%	+38%
G_{past_feed}	2930	+5%	+48%	-10%	+15%	-21%	+8%	-41%	-19%
G_{past_ecosys}	13500	-8%	+9%	-13%	-9%	-6%	+1%	-6%	-6%
G_{past_area}	16430	-6%	+16%	-12%	-5%	-9%	+2%	-13%	-9%
$G + B + G_{past\_feed}$	9990	+39%	+42%	+42%	+42%	+21%	+20%	+21%	+21%
$G + B + G_{past\_area}$	23500	+12%	+23%	+11%	+13%	+5%	+9%	+5%	+5%
Livestock only									
B	370	+51%	+43%	+51%	+49%	+22%	+11%	+19%	+24%
G_{irr}	330	+94%	+100%	+91%	+85%	+21%	+30%	+27%	+24%
G_{rf}	1960	+70%	+47%	+90%	+74%	+24%	+1%	+36%	+20%
G	2290	+74%	+55%	+90%	+76%	+24%	+5%	+34%	+21%
$G + B$	2670	+70%	+52%	+85%	+71%	+23%	+6%	+32%	+21%
$G + B + G_{past\_feed}$	5590	+36%	+50%	+35%	+42%	0%	+7%	-6%	+1%
$G + B + G_{past\_area}$	19100	+5%	+21%	+1%	+6%	-5%	+3%	-6%	-5%

3.3. *Regional relevance of water withdrawals and consumption*

Global values of water withdrawals and consumption are the aggregate of diverse dynamics on the regional scale (Fig. 6). Reduced demand for livestock commodities generally lowers total agricultural water consumption in all regions. However, regional Wd_{irr} and B are not very responsive to dietary changes – with the exception of Northern America. In Sub-Saharan Africa, water consumption and withdrawals in 2050 are projected to substantially surpass contemporary levels, reflecting the strong increase in population as well as per-capita food and livestock demand in all scenarios. The sensitivity of the interplay between pasture and cropping activities to livestock productivity gains (BASELINE and CATCH-UP scenarios relative to DIVERGENCE) is mirrored by the considerable shift of green water attributable to grazing (G_{past_feed}) to G on cropland. Management of remaining pastures is intensified, i.e. ET related to ecosystem services (G_{past_ecosys}) is strongly reduced (SI appendix, Fig. S13).

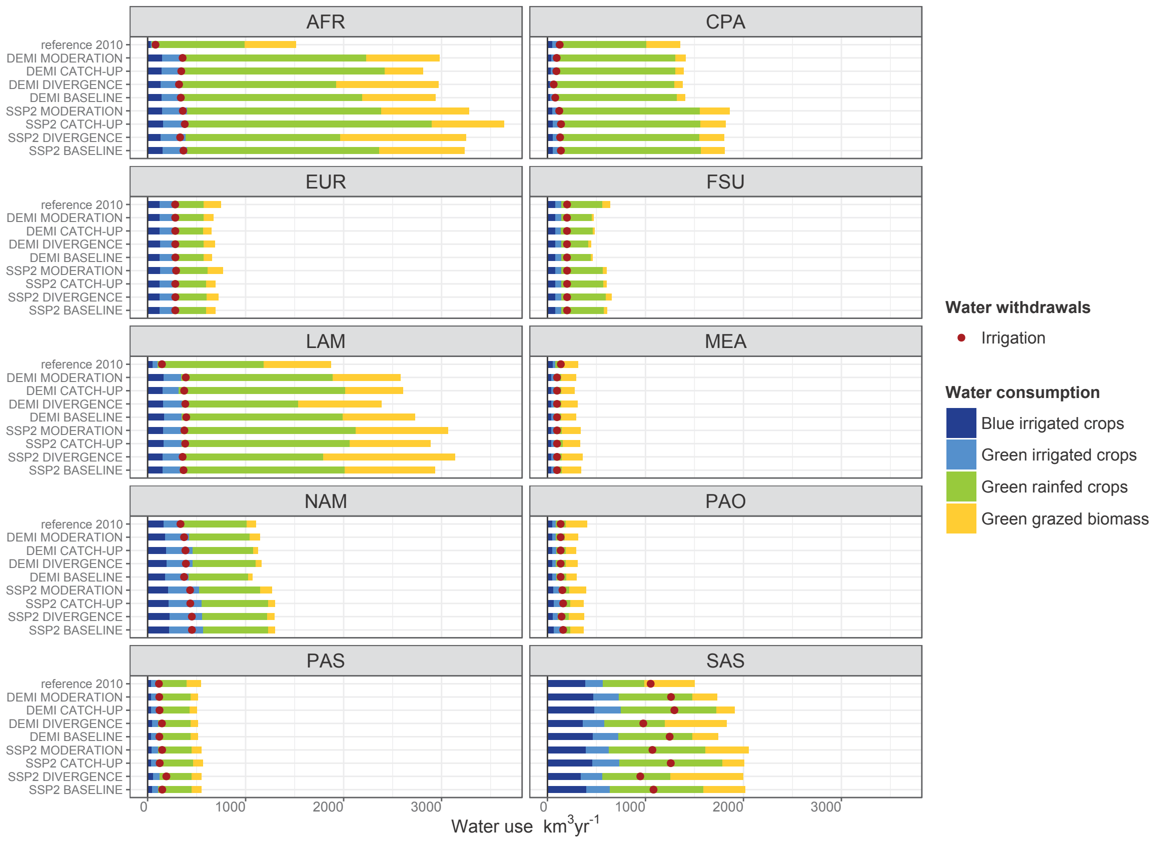

Fig. 6. Regional agricultural green (G) and blue (B) water consumption in km^{3}yr^{-1}. Red points indicate regional water withdrawals for irrigation (Wd_{irr}) in km^{3}yr^{-1}. The first bar in each panel (ref2010) indicates values for the reference year 2010. Scenario results are given for 2050. Note that water consumption on irrigated cropland also comprises green components (G_{irr}). Wd_{irr} accounts for conveyance losses due to water transport from source to field. Application of irrigation water to fields involves non-consumptive flows.

While expansion of cropland and irrigation in Sub-Saharan Africa goes along with a rise in area affected by high levels of water scarcity, extended cropping activities in Latin America pertain to areas more abounding in water. Moreover, growth in G_{past_feed} can be realized by higher grazing intensities in all scenarios except SSP2 DIVERGENCE, where a combination of higher demand for livestock products and lower livestock productivities involves an expansion of pastures. In South Asia, *G* and *B* strongly respond to the additional feed demand for crops induced by increasing livestock productivity. In the Middle East and North Africa, *B* and Wd_{irr} are not responsive to scenario assumptions and even decrease compared to 2010, due to severe scarcity of *RFWR* and a growing water demand from other sectors. In North America, the SSP2 baseline scenario entails an expansion of irrigated crop production compared to 2010. Yet, with decreasing consumption of animal-based products, this trend may partly be reversed.

3.4. Uncertainties in projected blue water consumption

To better elucidate constituents of *B* dynamics, we conduct a sensitivity analysis defining three additional scenario settings: a) *Unlimited water supply* to analyse the influence of resource scarcity; b) *Static irrigation water productivity* where, in contrast to our default setting, R&D investments improve land productivity but leave irrigation water per ton output (m^3ton^{-1}) constant, thereby increasing irrigation water demand per area (m^3ha^{-1}) linearly with yields; and c) *Exogenous yield trajectories* where all standard productivity and diet scenarios are calculated with identical regional yield growth trajectories, based on the endogenous crop yield trajectories from the SSP2 BASELINE scenario.

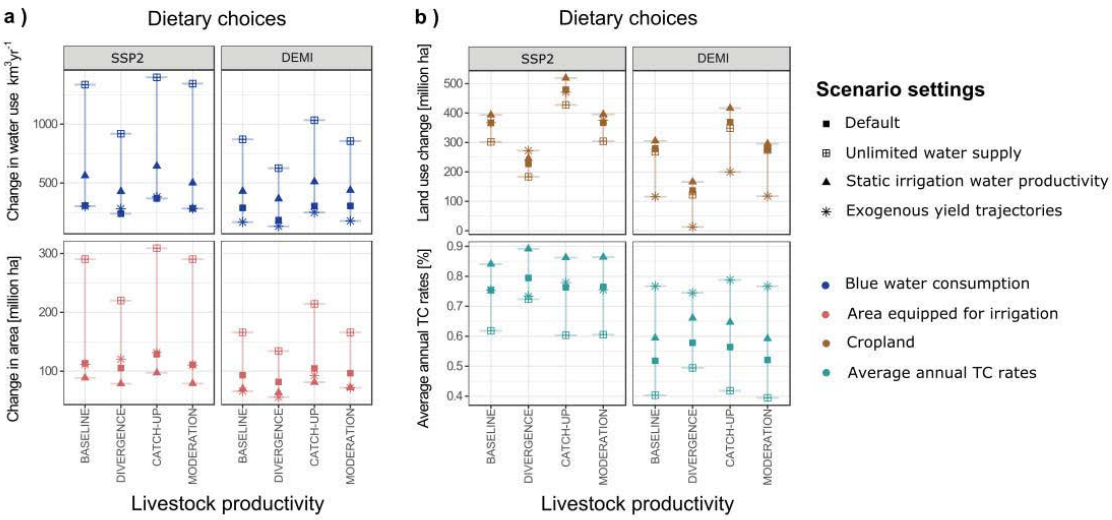

Fig. 7. Sensitivity analysis. Panel a) illustrates changes in global agricultural blue (*B*) water consumption in km^3yr^{-1} and in global area equipped for irrigation in million ha between 2010 and 2050. Panel b) shows changes in global cropland in million ha and average annual TC rates between 2010 and 2050.

Results of all diet and productivity scenarios assuming *Exogenous yield trajectories* accentuate the importance of technological innovation as a buffer in the whole food system, dampening the translation of demand-side signals into resource use. Under the *default* setting, a reduction of livestock products in diets attenuates the pressure in the food system, involving not only a general decline in the exploitation of natural resources (both land and water) but also lowering efforts to increase agricultural productivity. If technological innovation and improved management are presumed to be persistent under a dietary transformation towards less livestock products, we observe larger positive impacts in terms of mitigated land conversion and blue water use (reduction in *B* by 8-12%).

The assumption of *unlimited water availability* entails a substantial increase in irrigated area and B (Fig. 7a) due to the comparative advantage of expanding irrigation activities relative to cropland expansion and investments into other yield increasing innovations and management strategies (Fig. 7b). Although average annual rates of technological change (TC) further decline in the wake of reduced consumption of livestock products, both area equipped for irrigation and *B* are very sensitive to dietary changes (11-15% reduction of *B*, see Table 4).

Compared to the default setting, the assumption of *static irrigation water productivity* decreases potentials and therefore leads to low estimates of irrigated area. Since irrigation water is less productive to generate a high production volume, expansion of cropland together with R&D investments supersede irrigation in delivering growth in crop production, implying strongest increases in cropland across all sensitivity settings. In the case of static irrigation water productivity, both irrigation water demand and *B* are assumed to increase linearly with yield, therefore leading to higher estimates of *B* than in the default setting. Dietary changes lead to a reduction in *B* by 4-8%.

Table 4. Impacts of dietary changes on global blue (*B*) water consumption for all productivity scenarios under the default and additional model settings of the sensitivity analysis (changes in *B* (%) for DEMI diet scenarios relative to SSP2 diet scenarios in 2050).

Model settings	BASELINE	DIVERGENCE	CATCH-UP	MODERATION
Default	-1%	-4%	-5%	2%
Unlimited water supply	-15%	-11%	-11%	-15%
Static irrigation water productivity	-8%	-4%	-8%	-4%
Exogenous yield trajectories	-10%	-12%	-9%	-8%

4. Discussion

4.1. *Current blue and green water consumption*

It has been noted earlier that an analysis of livestock systems offers substantial scope to understand and increase total agricultural water productivity (Cook et al., 2009; Herrero et al., 2009; Peden et al., 2007; Steinfeld et al., 2006). However, few studies are available that quantify the contribution of livestock production to green (G) and blue (B) water consumption at the global scale. A combined blue-green approach to assess future agricultural water use facilitates the identification of land-water related trade-offs and captures other than blue-only strategies to meet rising water requirements for food production, like expansion and intensification of rainfed cropland and relocation of agricultural activities to more water-abundant regions (Rockström et al., 2007, 2009). Our findings underline the relevance of exploring links between livestock and water, with one-third of crop water consumption being attributable to feed production.

Table 5. Estimates of global green (G) and blue (B) water consumption and agricultural water withdrawals (Wd_{irr}) in $km^3\ yr^{-1}$. G on cropland is differentiated between rainfed (G_{rf}) and irrigated cropland (G_{irr}). On pastures, G is differentiated between evaporation on total pasture area (G_{past_area}) and G attributable to grazed biomass (G_{past_feed}).

		Our estimates		Rost et al. (2008)	Hanasaki et al. (2010)	Molden (2007)	Other estimates
		2000	2010	1971-2000	1985-1999	2000	Not specified
Total agriculture							
Cropland	Wd_{irr}	2570	2610	1161-2555		2630	2200-3800[c]
	B	1010	1020	600 - 1258	1530[a]	1570[a]	
	G_{irr}	720	790	307 - 325[a]	850[a] -1720[b]	650[a]	
	G_{rf}	4380	5250	6936 - 6949[b]	4700[a] - 7820[b]	4910[b]	
	G	5100	6040	7242 -7273	5550[a]-9540[b]	5560	
	$G + B$	6100	7070	7874 - 8501	7080[a]-11070[b]	7130	6390[d]
Pasture	G_{past_feed}	2590	2930			840	913[e]
	G_{past_area}	16520	16430	8191 - 8258	12960		5800[e]-20400[f]
Livestock only							
Cropland	$G + B$	2170	2670			1312	1463[g]

a: Cropping period.
b: Throughout the year.
c: Wisser et al. (2008).
d: Chapagain (2006).
e: Mekonnen and Hoekstra (2010), estimate for 1996-2005.
f: Postel (1998), estimate for 1995.
g: Falkenmark and Rockström (2004), estimate for 1999.

Our estimate of 2170 $km^3 yr^{-1}$ water consumed by cropland feed in 2000 is higher than previously suggested (Table 5), due to a high contribution of cultivated forage (e.g. alfalfa, rye grass and forage maize), inclusion of all major feed categories (including food industry by-products like soy meal) and full feed energy balances. Mekonnen and Hoekstra (2010) estimate that consumptive water use of feed crops accounts for 1463 $km^3 yr^{-1}$ (1996-2005) and that 6.2% of livestock related water consumption is of blue origin, based on virtual water calculations. Since also our estimates for G attributable to cropland feed production and grazing are higher, our calculations lead to similar contribution of 7% blue water to the livestock water footprint. Our estimate for G (5100 $km^3 yr^{-1}$) is at the lower end of earlier estimates, owing to optimality of land allocation patterns regarding cost-effectiveness and resource constraints inherent in our modelling approach, whereas estimated B (1010 $km^3 yr^{-1}$) is well within the range of 600-1570 $km^3 yr^{-1}$ of previous studies.

Combining water consumed on cropland for animal feed production with G_{past_feed}, consumptive water use of livestock amounts to 56% of total agricultural water consumption, which is higher than the 45% estimated by Zimmer and Renault (2003). Thus, grazing land is not only from the land but also from the water perspective an important resource. Since impacts of grazing on the hydrological cycle are small compared to irrigated agriculture (Peden et al., 2007; Steinfeld et al., 2006), the relevance of water consumption on grazing land is better described by the opportunity costs of involved precipitation water (and land) as by actual water depletion. Differentiation between the type of land (cropland or pasture) and water use (green or blue) may shed some light on the implications of involved resource use, since the opportunity costs and environmental impacts of cropland and blue water are typically higher.

4.2. Livestock futures and the water challenge of agricultural production

Dietary changes are a frequently discussed option to meet the water challenge of future food supply and alleviate water scarcity (Gerten et al., 2011; Jalava et al., 2014; Liu and Savenije, 2008; Marlow et al., 2009; Mekonnen and Hoekstra, 2010; Schmitz et al., 2013; Steinfeld et al., 2006). However, recommendations to reduce meat consumption in order to preserve water resources are often based on static inventories of current livestock related water consumption and resulting virtual water content (*VWC*) of livestock products (Jalava et al., 2014; Mekonnen and Hoekstra, 2010; Steinfeld et al., 2006), or informed by simplified assumptions on livestock feeding and related water use (Gerten et al., 2011; Zimmer and Renault, 2003). Adding to the existing literature, our assessment of the water-saving potential of dietary changes does not only consider alternative assumptions on future livestock productivity, thereby altering feed and water use per product over time, but also comprises secondary effects like changes in R&D investments, land-use dynamics and adjustments in trade flows (SI appendix B). Our results emphasize the outstanding importance of economic processes for evaluating sustainability issues and reveal the non-linearity of systems' responses to demand- and supply side changes.

The potential of a demitarian diet to lower pressures on freshwater resources is indeed influenced by productivity trajectories, but, as the sensitivity analysis highlights, even more by other factors that indirectly influence dynamics within the food system. Especially assumptions on availability of blue water, dependence of investments in research and development (R&D) from demand-side pressures and economic competitiveness of irrigation determine the water-saving potential of dietary changes. Assuming limited water supply (*RFWR* only), improvements in irrigation water productivity and feedbacks between R&D investments and biomass demand, *B* is less responsive to reduced consumption of livestock products than rainfed agriculture. The latter observation also confirms findings by Jalava et al. (2014) that lower protein supply from livestock products (at most 50% and 12.5% respectively of total protein supply) has a larger effect on *G* (-6% to -15%) than on *B* (-4% to -9%).

Consequently, irrigated agriculture will continue to play an important role, even if demand for crops strongly declines, since in many locations deployment of irrigation is constraint by water availability and below optimum regarding economic and agronomic considerations. Moreover, areas already equipped for irrigation are in general attractive for agricultural production, given sufficient water availability, and less prone to being abandoned compared to rainfed cropland in the same location. As long as there are no opportunity costs (e.g. use from other sectors) or water protection policies such as pricing, the model is inclined to use accessible water wherever the soil water deficit below optimal plant growth is large enough to make irrigation economically competitive to other yield increasing management options. The higher sensitivity of rainfed agriculture to dietary changes indicates that it is primarily land that is spared and only secondarily freshwater.

The balance between water consumption attributable to cropland and grassland, as well as between green and blue flows, is strongly influenced by livestock productivity via changes in feed efficiency and composition. Assuming the continuation of low historical productivity trajectories in some regions, we observe an increase of water consumption attributable to grazing to fulfil food water requirements, which goes along with expansion of pasture into pristine areas, entailing loss of natural vegetation and carbon emissions. Intensification of low productive systems involves a shift from grassland/green water resources to cropland/blue water resources. Analogously to land use change, where conversion from pastures to cropland might reduce pressures on natural ecosystems, a shift from green water consumption from grazing to cropping may unlock additional water resources other than irrigation. From the perspective of maintaining ecosystem services, biodiversity (Alkemade et al., 2013) and carbon sequestration (Conant et al., 2001; Don et al., 2011; Popp et al., 2014) on agricultural land, pasture-to-cropland conversion may also be seen critical and is likely to affect hydrological processes through e.g. higher run-off from cropland (Peden et al., 2007).

Although increases in livestock productivity are beneficial with regard to feed conversion efficiencies, resulting decrease in feed demand is less than proportionate, due to higher competitiveness of some regions' livestock sectors and interregional reallocation of production. Especially in Latin America, efficiency gains lead to a growth in production and export volume. Owing to higher feed demand from cropland, an intensification of livestock production increases blue water use which may jeopardize human water security and environmental flow requirements of aquatic ecosystems, e.g. in India and East Africa, where already today pressures from feed production on land and water resources are high (Herrero et al., 2010). However, pressures on land are diminished, since cropland can expand into pastures, thereby sparing natural vegetation and avoiding carbon emission from deforestation. Water protection policies such as pricing mechanisms or water rights cap-and-trade schemes could therefore be feasible with only minor implications for land-related trade-offs (Bonsch et al., 2015).

Improving low productivity levels is often considered beneficial both regarding environmental and social impacts like improved food security and livelihoods (Herrero et al., 2009, 2010; Steinfeld et al., 2006; Weindl et al., 2015). In contrast, there is an increasingly critical debate about intensification at high productivity levels since large-scale industrial livestock operations are associated with heavy nutrient loadings, pollution of terrestrial and aquatic ecosystems through excessive use of nitrogen and pesticides as well as pathogens, conflicts with animal welfare, and loss of biodiversity (Franzluebbers, 2007; Lemaire et al., 2014; Russelle et al., 2007; Tilman et al., 2002). As productivity reductions in the MODERATION scenarios have only minor effects on type and magnitude of agricultural water consumption, measures aimed at abating side-effects of industrial livestock operations that might impede productivity could be successful without substantially increasing water requirements to produce food.

4.3. Assumptions and limitations

Vörösmarty et al. (2005) and Rost et al. (2008) suggest that a substantial share (16-33% and 55%) of Wd_{irr} (400-800 km^3yr^{-1} and 1400 km^3yr^{-1}) exceeds locally accessible and renewable freshwater supplies and draws e.g. from non-renewable or oceanic sources such as fossil groundwater and water from desalination plants (Rost et al., 2008). Accounting only for renewable freshwater resources we may underestimate B and Wd_{irr}, especially in major irrigation countries like India, China and the Unites States. Moreover, water withdrawn especially by non-agricultural sectors partially re-enters rivers and is, after wastewater treatment, available for downstream use (Flörke et al., 2013). We assume inelastic water demand from non-agricultural sectors which limits the de-facto water availability for agriculture. On the other hand, we may overestimate accessibility of freshwater since the balance between water supply and demand is established on the level of 1000 simulation units, thus assuming that water can freely be allocated within rather large areas. Moreover, in this analysis we do not consider climate change impacts on the hydrological cycle and on crop yields.

Although our analysis tries to cover several aspects of water scarcity, there is a multitude of relevant aspects of the livestock-water-nexus that are not considered. It is widely acknowledged that freshwater ecosystems and river biodiversity are in a state of crisis (Falkenmark and Molden, 2008; Vörösmarty et al., 2010). Knowledge of relative water demand alone is not sufficient to assess how human water use may threaten freshwater ecosystems. Environmental flow requirements sustaining river ecosystems vary by location (Bonsch et al., 2015; Hanasaki et al., 2008; Smakhtin et al., 2004), stressors are very diverse (watershed disturbance, water resource development, pollution) and may partially be abated by considerable investments in water technologies, as it has been successfully done by affluent nations to alleviate threats to human water security (Vörösmarty et al., 2010). Agricultural activities do not only disturb hydrological processes by water withdrawals, but also by water contamination, deforestation and inappropriate land use (Peden et al., 2007). Our focus on water consumption linked to feed production neglects the implications of livestock for water pollution, being especially relevant in the context of highly intensive livestock production systems (Carvalho et al., 2010; Russelle and Franzluebbers, 2007). Especially nitrogen and phosphorus surpluses represent a major threat to water quality and aquatic ecosystems leading to eutrophication with severe impacts on the mix of aquatic plants, habitat characteristics as well as aquaculture and fisheries (Grizzetti et al., 2011; Steinfeld et al., 2006).

5. Conclusion

Both human and animal diets matter for limiting further disruptions of hydrological processes. We show that intensification of currently low-productive livestock systems will substantially alter both magnitude of water consumption and the balance between different types of water and land use. Although effects on total livestock-related water consumption are beneficial, an increase in blue water use could negatively affect human water security and environmental flows. Furthermore, results indicate that moderate productivity reductions in intensive systems are possible without increasing total crop water consumption, thereby opening up leeway to abate impacts from large-scale industrial enterprises, such as pollution of aquatic ecosystems through heavy nutrient loadings, pesticides and pathogens. A continuation of low productivity trends heavily relies on green water consumption related to expanding pastures, involving further land conversion at the expense of natural ecosystems.

The magnitude of the total livestock water footprint gives cause for serious concern regarding the water implications of our food choices. Dietary changes have considerable impacts on agricultural water consumption, but mainly of green origin, thereby also relaxing pressures on land. Direct positive effects on blue water are prone to high uncertainties and depend on the interplay of biophysical and socio-economic conditions. Neither dietary changes nor a transition of livestock production systems along the investigated productivity trajectories will solve the water challenge of future food supply if not accompanied by water protection policies, such as water pricing or water rights cap-and-trade schemes. Even the lowest estimate of future agricultural blue water consumption still represents an increase by 19% compared to current levels. As a consequence, it is important to combine demand-side policies aiming at a transformation of consumption patterns with supply-side interventions, capacity building, dedicated water policies and agricultural R&D to protect aquatic ecosystems and mitigate unsustainable water use that might compromise livelihoods of future generations.

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Livestock production and the water challenge of future food supply: implications of agricultural management and dietary choices

Supplementary information (SI Appendix)

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Appendix A. Extended methodology

A.1. MAgPIE (Model of Agricultural Production and its Impact on the Environment)
MAgPIE is a global economic land and water use model which is linked to the Lund-Potsdam-Jena dynamic global vegetation and water balance model with managed land (LPJmL) (Bondeau et al., 2007; Müller and Robertson, 2014). It integrates geographically explicit information on land quality and biophysical constraints into an economic decision making process (Lotze-Campen et al., 2008). Possible future developments are simulated in a recursive dynamic mode by minimizing a nonlinear global objective function for each 10-yr time step. The simulation period starts in the calibration year 1995, which allows for a consistency check and benchmarking between projections and statistical data since 1995. Due to computational constraints, geographically explicit information on 0.5 degree resolution was aggregated to 1000 simulation units for this study, based on a k-means clustering algorithm (Dietrich et al., 2013). The core model code is written in the GAMS (Generalized Algebraic Modelling System) programing language using the CONOPT non-linear programming solver. Simulations are generated with model-revision 10007. LPJmL input data are based on simulations submitted to the Geoportal (http://geoportal-glues.ufz.de) of the GLUES project (Global Assessment of Land Use Dynamics, Greenhouse Gas Emissions and Ecosystem

Services), a scientific coordination and synthesis project of the "Sustainable Land Management" research programme funded by BMBF (German Federal Ministry of Education and Research).

In the initial year 1995 of the simulation period, MAgPIE is calibrated to a spatially-explicit dataset of the following land pools: cropland, permanent pasture, forest (semi-natural forest including forestry and undisturbed natural forest), urban areas (static over time), and other land (snow, ice, other natural vegetation) (Krause et al., 2013). Accounting for forest area designated for wood production (about 30% of the initial global forest area) and forests in protected areas which represent about 12.5% of global forests (FAO, 2010), parts of semi-natural and undisturbed natural forests are excluded from conversion into agricultural land. Natural vegetation or pasture can only be converted into cropland if the land is at least marginally suitable for rain-fed crop production according to climate, topography and soil type according to the Global Agro-Ecological Assessment (GAEZ) methodology on land suitability (Fischer et al., 2002; Velthuizen et al., 2007).

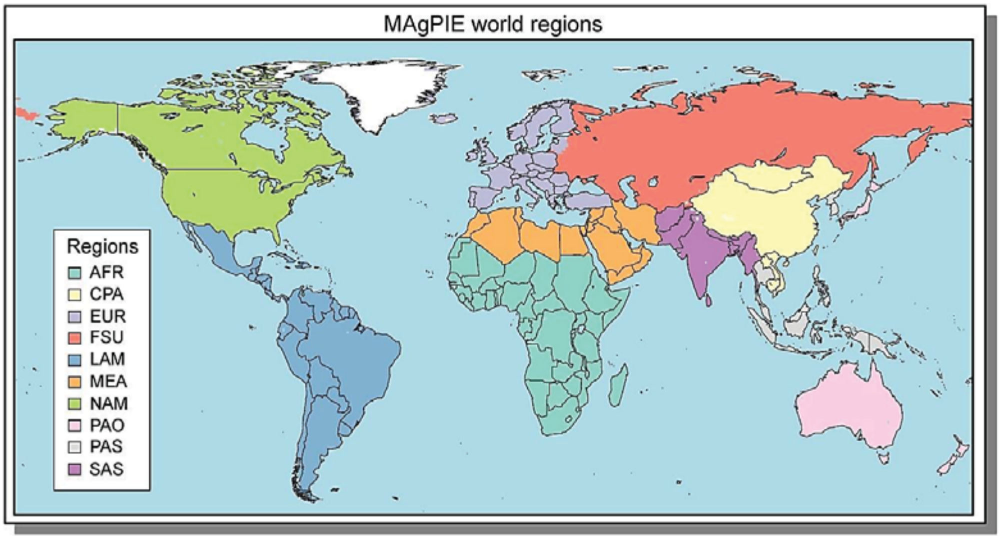


Fig. S1. MAgPIE world regions (AFR: Sub-Saharan Africa; CPA: Centrally-planned Asia incl. China; EUR: Europe incl. Turkey; FSU: Former Soviet Union; LAM: Latin America; MEA: Middle East/North Africa; NAM: North America; PAO: Pacific OECD, i.e. Japan, Australia, New Zealand; PAS: Pacific Asia; SAS: South Asia incl. India).

Agricultural land use in MAgPIE is induced by 17 cropping activities (15 food crops, 1 fibre crop, and 1 forage crop) allocated to cropland and by livestock grazing on permanent pasture, required to satisfy demand for food, feed, seed and materials. Feed demand also includes food industry byproducts (molasses, brans and oil cakes) which are generated in the manufacturing of harvested crops into processed food. In the model, the production of byproducts is calculated by multiplying the total domestic supply of associated primary crops with a crop-specific conversion factor (Bodirsky et al., 2012). Food industry byproducts are allocated to different world regions via trade, where the partition of resulting domestic supply of food industry byproducts into different uses (food, feed and material) is parametrised according to the FAO Commodity Balance Sheets (CBS) (FAOSTAT, 2013). If the demand for byproducts is higher than domestic supply, byproducts can be imported or the model can provide food or forage crops of at least the same nutritional value as substitute. While in the model, many residual feed components, e.g. crop residues or food waste, come for free in terms of resource use, oilcakes and especially soymeal are a very valuable feed. Accordingly, we follow the approach by Steinfeld et al. (2006) and attribute 66% of resources used to produce soybean to the respective feed use of soymeal, which is based on the soymeal value fraction in soybean production (Chapagain and Hoekstra, 2003; Steinfeld et al., 2006).

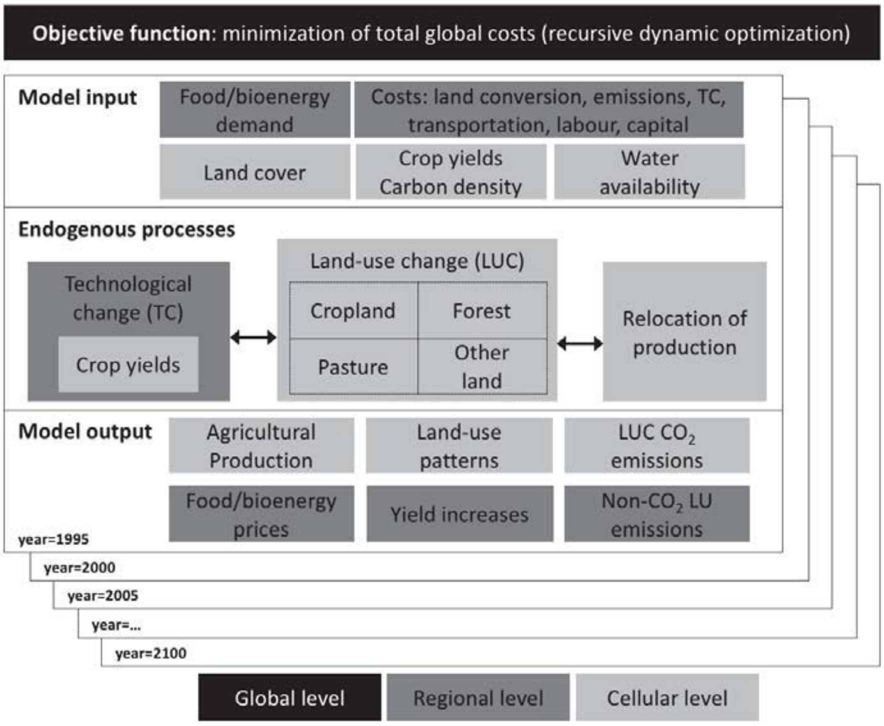


Fig. S2. Schematic representation of the MAgPIE model.

Spatial distribution of crops and pasture within current agricultural land as well as the trade-off between land expansion and improvements of both crop yields and pasture productivity is guided by the cost-effectiveness of resulting land use patterns. Based on historical trade patterns and cost competitiveness, global demand for agricultural commodities is allotted to the supply regions via endogenous trade flows which are implemented on the basis of flexible minimum self-sufficiency ratios and two virtual trading pools (Schmitz et al., 2012). Assuming medium rates of trade liberalization, global trade barriers are relaxed by 5% per decade, which is less than observed liberalization trends (Schmitz et al., 2012). Thus, an increasing share of commodities can be traded according to comparative advantages of supply regions. Within a region, the model chooses the land-use patterns according to cost-competitiveness, taking into account biophysical conditions like potential yields and water availability, as well as economic conditions like management and transport costs.

Following cost types are integrated into the economic decision-making process of land and water use: Production costs per area are derived from the Global Trade, Assistance, and Production (GTAP) database (Narayanan and Walmsley, 2008) and contain factor costs for labour, capital and intermediate inputs (Dietrich et al., 2014). Through investments in technological change, the model can endogenously increase yields of both irrigated and rainfed crops (Dietrich et al., 2012, 2014). Expansion of cropland is associated with land conversion costs, which are estimated on the basis of marginal access costs from the Global Timber Model (Sohngen et al., 2009) and account for basic infrastructure investments and preparation of converted land (Krause et al., 2013; Popp et al., 2011). Irrigation costs include investment costs for establishing new irrigation infrastructure, which are based on Worldbank data (Jones, 1995) and annual costs for operating irrigation systems (Bonsch et al., 2014). Following an approach by Calzadilla et al. (2011), the rent associated with irrigation water application is calculated from the GTAP land rent (Narayanan and Walmsley, 2008) and used as a proxy for the operation and maintenance costs of irrigation infrastructure. Lastly, the global objective function involves intraregional transport costs, thus integrating information about market access into the decision process where to allocate agricultural activities. Expenditures for transportation depend on the distance of the production site to markets, the quality of the infrastructure (both based on a detailed data set on travel time (Nelson, 2008) as well as average transport costs for different commodities based on GTAP (Narayanan and Walmsley, 2008).

MAgPIE is applied for a broad spectrum of research questions like climate change mitigation options (Humpenöder et al., 2014; Popp et al., 2011, 2014; Stevanović et al., 2017), nutrient cycles (Bodirsky et al., 2012, 2014) , bioenergy (Bonsch et al., 2014; Lotze-Campen et al., 2014), climate impacts (Stevanović et al., 2017; Weindl et al., 2015), water scarcity (Bonsch et al., 2015; Schmitz et al., 2013), and trade (Biewald et al., 2014; Schmitz et al., 2012). In combination with the energy–economy–climate model ReMIND (Luderer et al., 2013), the ReMIND/MAgPIE framework (Popp et al., 2011) was amongst the Integrated Assessment Models (IAMs) that were applied for the translation of the narratives of the Socio-Economic Pathways (SSPs) into quantitative projections and for the systematic interpretation of the different SSPs in terms of possible land-use (Popp et al., 2017) and energy futures (Bauer et al., 2017). A comprehensive study exploring differences in land-use change trajectories up to 2050 across global agro-economic models including MAgPIE (four partial and six general equilibrium models) was carried out by Schmitz et al. (2014).

A.2. Livestock in MAgPIE: Supplementary information

Supply of livestock products (ruminant meat, whole-milk, pork, poultry meat and eggs) is realized by five animal food systems (beef cattle, dairy cattle, pigs, broilers and laying hens) that further account for different animal functions (reproducers, producers and replacement animals). There is no one-to-one correspondence between livestock products and animal food systems, e.g. both beef and dairy cattle systems generate ruminant meat. The parameterization of the livestock sector is based on FAO Commodity Balance Sheets (CBS) (FAOSTAT, 2013) containing data on production, trade and utilization of agricultural commodities. The initial parameterization of the livestock sector is consistent with FAO statistics (FAOSTAT, 2013) regarding livestock production, livestock productivity and feed use of food crops and food industry byproducts (like molasses, brans and oil cakes).

Following the methodology of Wirsenius (2000), our approach is based on system-specific feed energy balances and comprises the estimation of biomass available as feed on country-scale (including statistically not documented feed resources like crop residues) and the distribution of available feed to animal food systems. We downscale regional feed energy requirements per output, as estimated by Wirsenius (2000) for each animal function and animal food system, to the country scale, using national numbers on livestock productivity from FAOSTAT. The feed energy requirements are based on standardized bio-energetic equations and major productivity parameters like live-weight, live-weight gain and reproduction rate, and include the minimum energy requirements for maintenance, growth, lactation, reproduction and other basic biological functions of the animals (expressed in metabolizable energy (ME), and in the case of ruminants also net energy (NE) for maintenance (NE.m), growth (NE.g) and lactation (NE.l)). In addition, they comprise a general allowance for basic activity and temperature effects. Maintenance energy requirements for grazing cattle may be 10-20% higher under best grazing conditions and up to 50% higher for extensive pastures with long walking distances, compared to penned animals (NRC 1996). We therefore increase the maintenance requirements by additional 10-20%, depending on the productivity of ruminant production systems.

By multiplying country-specific livestock production data with feed energy requirements per product, we obtain feed energy demand on country resolution. In addition to the demand, the establishment of feed energy balances requires information on country-specific feed energy supply. The CBS only comprise data on the production, trade and utilization (e.g. feed use) of food commodities as well as food industry byproducts like molasses, brans and oil cakes. We therefore supplement the feed use data from the CBS by production data on forage crops (FAOSTAT, 2013) and by estimates of feed use covering other categories like crop residues and food waste, the latter being calculated on the basis of regional intake to supply shares and feed assignment rates from Wirsenius (2000). Estimates of the amount of crop residues used as feed are based on crop-type specific plant growth functions and harvest indices of food crops (Bodirsky et al., 2012; Eggleston et al., 2006; Lal, 2005; Wirsenius, 2000) as well as recovery rates and assignment rates for feed use (Krausmann et al., 2008; Wirsenius, 2000).

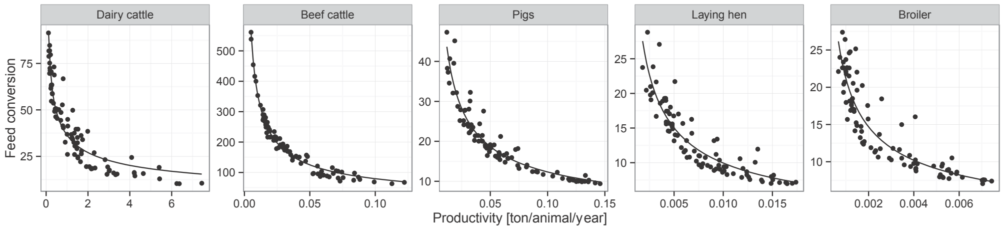
The distribution of the described expanded data base on feed supply at country resolution to single animal food systems and animal functions is realized by an optimization routine written in GAMS, that minimizes the deviation of resulting energy content of feed intake for ruminant systems from productivity-dependent guidelines (NRC, 1989, 1996; Wirsenius, 2000), and simultaneously minimizes the use of two balancing feed categories in the feed energy balances: occasional feed (not statistically documented feed resources, e.g. scavenging) as balancing post for monogastric systems and grazed or browsed biomass for ruminant systems. The feed energy balances are established on the basis of feed-specific energy contents (expressed in ME, NE, NE.m, ME.g and NE.L) (Wirsenius, 2000) and differentiate 16 food crop and 3 forage (only separated within the feed distribution model) crop groups, 3 groups of crop residues, 4 groups of food industry byproducts (oil cakes, molasses, distillers grains and brans), food waste, occasional feed as well as grazed or browsed biomass.

By distributing the available feed at country level to animal food systems according to their feed energy demand and dividing resulting dry matter feed use by the production volume of the respective systems, we obtain both estimates for feed conversion F_C (total feed input per product output in dry matter) and feed baskets F_B (demand for different feed types per product output in dry matter) across different animal food systems and countries.

A.3. Non-linear regression models for feed conversion and feed composition

To facilitate projections of feed conversion F_C and feed baskets F_B, we create regression models with livestock productivity P (annual production per animal [ton fresh matter/animal/year]) as predictor, which permit the construction of productivity dependent livestock feeding scenarios. For beef cattle, pigs and broilers, P is defined as meat production per animals in stock (e.g. total cattle herd) and for dairy cattle and laying hen as milk or egg production per producing animals (e.g. milk cows). Data processing and statistical analyses are conducted applying the programming language and statistical software R (R Core Team, 2015). Estimation of the parameters of the non-linear regression models is performed employing function *nls* of package *stats*. In order to test resulting models against data with linear regressions, we use function *lm* of package *stats*.

a)



b)

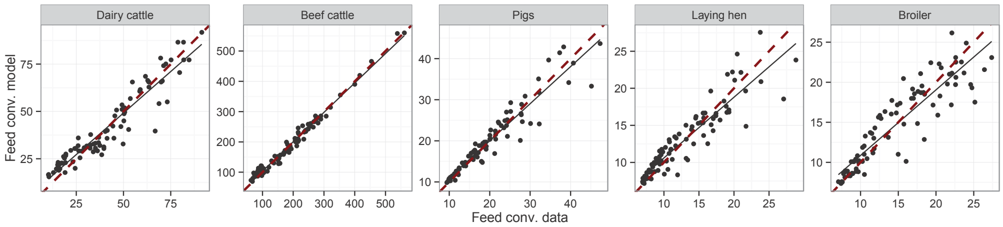


Fig. S3. Feed conversion F_C (defined as total feed input per product output in dry matter) for major animal food systems plotted against livestock productivity P in 1995 and model estimation with formula $y \sim \alpha x^{\beta}$ (a). Comparison of data and model estimates with linear regression (solid line; see Table S2 for statistical properties) and 1:1 line (dashed line) (b).

For feed conversion F_C, best performance was obtained using a power function to describe the functional relation between F_C and livestock productivity P as predictor variable: $F_C(P) = \alpha P^{\beta}$. We included only countries into our analysis that represent at least 0.001% of global production related to each of the five livestock commodities under consideration. Fig. **S3**a) displays the model estimation for F_C. For all parameters, p-values of the t-tests are statistically highly significant (see Table S1 for more information on regression parameters). Fig. S3b) illustrates the overall fit of the models, which are statistically highly significant with a coefficient of determination of 0.98, 0.90. 0.91, 0.82 and 0.83 for beef cattle, dairy cattle, pig, broiler and laying hen systems (see Table S2 for more information on statistical properties of the linear regressions between model estimates and data).

Table S1. Regression parameters for feed conversion F_C with formula $y \sim \alpha x^{\beta}$. Significance levels for p-values are denoted by (***): p < 0.001, (**): p ∈ [0.001, 0.01), (*): p ∈ [0.01, 0.05), (.): p ∈ [0.05, 0.1).

Animal food system	Parameter	Value	SE	p-value
Beef cattle	α	17.5262	0.6874	< 0.001 (***)
	β	-0.6556	0.0092	< 0.001 (***)
Dairy cattle	α	36.3321	0.8421	< 0.001 (***)
	β	-0.4256	0.0170	< 0.001 (***)
Pigs	α	3.1242	0.2226	< 0.001 (***)
	β	-0.5963	0.0201	< 0.001 (***)
Broiler	α	0.5584	0.1088	< 0.001 (***)
	β	-0.5262	0.0297	< 0.001 (***)
Laying hen	α	0.6445	0.1016	< 0.001 (***)
	β	-0.5942	0.0292	< 0.001 (***)

Table S2. Statistical properties of regression models for feed conversion F_C. Significance levels for *p*-values are denoted by (***): p < 0.001, (**): p ∈ [0.001, 0.01), (*): p ∈ [0.01, 0.05), (.): p ∈ [0.05, 0.1).

Animal food system	Intercept	Slope	R^2	*p*-value	F-statistics
Beef cattle	6.3597	0.9706	0.98	< 0.001 (***)	4830
Dairy cattle	5.2825	0.8775	0.90	< 0.001 (***)	768
Pigs	1.9533	0.9028	0.91	< 0.001 (***)	878
Broiler	2.6781	0.8186	0.82	< 0.001 (***)	391
Laying hen	2.3940	0.8202	0.83	< 0.001 (***)	427

Regarding feed composition F_{comp}, we tested several alternative groupings of different feed types to reveal a relationship between the share of these groups within the feed baskets F_B and livestock productivity P. For cattle food systems, we observe best performance for F_{comp} defined as the share of crop residues, occasional feed such as scavenging and grazed biomass within the feed rations. For pigs, best performance was apparent for defining F_{comp} as the complement of primary food items in pig feed baskets, i.e. the share of food waste, dedicated forage crops, occasional feed like scavenging, food industry by-products and crop residues within feed rations.

In the case of feed composition F_{comp}, we use an additional proxy parameter in our analysis. What type of biomass is used to feed animals is to a certain extent influenced by universal aspects (e.g. the need for more energy-rich feed at higher productivity levels), whereas other aspects are strongly influenced by geographical location (e.g. availability and costs of permanent pasture compared to cropland feed, agro-ecological and climatic conditions that favour selected feed items; socio-cultural determinants etc.). Using a single global function for describing the relationship between feed composition and livestock productivity inevitably entails a (possibly large) source of inaccuracy. Incorporation of spatial heterogeneity and climatic conditions into the analysis is facilitated by considering Koeppen-Geiger climate zones. For each country, we calculate the share of population living in four aggregated groupings of climate zones (Table S3), using a comprehensive data set downloaded from Portland State University (2015).

Table S3. Grouping of climate zones.

Group	Koeppen-Geiger climate zones
CTrop	Tropical rainforest climate (Af), Monsoon variety of tropical rainforest climate (Am), Tropical savannah climate (Aw)
CArid	Steppe climate (BS), Desert climate (BW)
CTemp	Mild humid climate with no dry season (Cf), Mild humid climate with a dry summer (Cs), Mild humid climate with a dry winter (Cw)
CCold	Snowy-forest climate with dry winter (DW), Snowy-forest climate with a moist winter (Df), Polar ice climate (E), Highland climate (H)

We test several alternatives to calculate the share of population living in one aggregated climate group ζ based on the groupings *CTrop, CArid, CTemp* and *CCold*, that can be used as a proxy to explain spatial heterogeneity of feed composition. Best performance is achieved by defining $\zeta \coloneqq CArid + CCold$ as aggregated climate group for cattle systems and by $\zeta \coloneqq CCold$ for pigs. For weighted non-linear regression models, we apply the following functional relationship F_{KG} for feed composition F_{comp}, defined as the linear combination of two asymptotic functions of P with the climate-zone specific factor ζ:

$$F_{KG}(P) = \zeta * \left(1 - \frac{\alpha P^3}{(0.1 + \alpha P^3)}\right) + (1 - \zeta) * \left(1 - \frac{\beta P^3}{(0.1 + \beta P^3)}\right).$$

a) **b)**

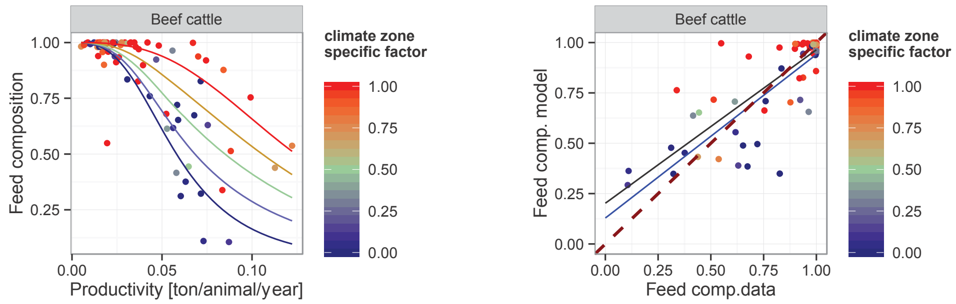


Fig. S4. Feed composition F_{comp} (defined as share of crop residues, occasional feed and grazed biomass in feed baskets) for beef cattle systems plotted against livestock productivity P in 1995 and model estimation F_{KG} (a). Comparison of data and model estimates with weighted linear regression (solid blue line with green shaded area, see Table S5 for statistical properties) and unweighted linear regression (solid black line with grey shaded area) as well as 1:1 line (dashed line) (b).

Country-level shares of crop residues, occasional feed and grazed biomass within feed baskets of beef and dairy cattle are presented together with the respective model estimation by Fig. S4 and Fig. S5. Table S4 shows estimated values for parameters α and β, as well as *p*-values of the *t*-tests. Weighted linear regressions between model estimates and data are statistically highly significant with a coefficient of determination of 0.84 and 0.71 for the beef cattle and dairy cattle system (see Table S5 for more information on statistical properties).

a) **b)**

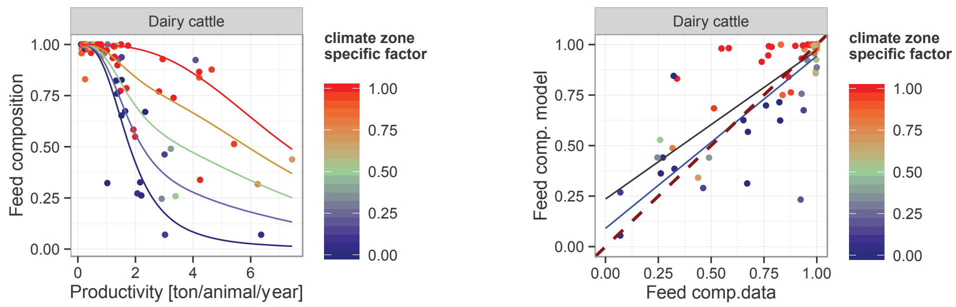


Fig. S5. Feed composition F_{comp} (defined as share of crop residues, occasional feed and grazed biomass in feed baskets) for dairy cattle systems plotted against livestock productivity P in 1995 and model estimation F_{KG} (a). Comparison of data and model estimates with weighted linear regression (solid blue line with green shaded area, see Table S5 for statistical properties) and unweighted linear regression (solid black line with grey shaded area) as well as 1:1 line (dashed line) (b).

Fig. S6a) shows country-level shares of food waste, dedicated forage crops, occasional feed, food industry by-products and crop residues within the feed baskets of pigs as well as the model estimation which depends on the climate-zone specific factor ζ. Parameters of the weighted non-linear regression were determined with high significance (see Table S4 for more information on parameter values, SE and *p*-values). The overall fit of the model, as illustrated by Fig. S6b), is statistically highly significant with a coefficient of determination of 0.67 (see Table S5 for more information on statistical properties of the weighted linear regression between model estimates and data).

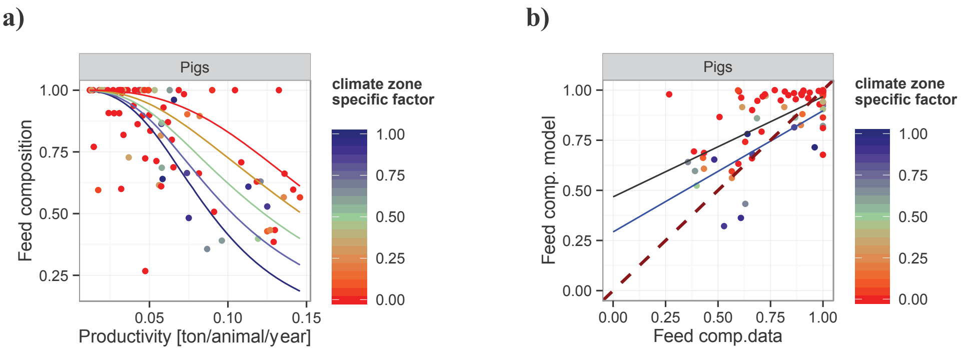


Fig. S6. Feed composition F_{comp} (defined as share of food waste, dedicated forage crops, occasional feed, food industry by-products and crop residues) for pig systems plotted against livestock productivity P in 1995 and model estimation F_{KG} (a). Comparison of data and model estimates with weighted linear regression (solid blue line with green shaded area, see Table S5 for statistical properties) and unweighted linear regression (solid black line with grey shaded area) as well as 1:1 line (dashed line) (b).

Table S4. Regression parameters for feed composition F_{comp} using a linear combination of two asymptotic functions of P with the climate-zone specific factor ζ. Significance levels for *p*-values are denoted by (***): p < 0.001, (**): p ∈ [0.001, 0.01), (*): p ∈ [0.01, 0.05), (.): p ∈ [0.05, 0.1).

Animal food system	Parameter	Value	SE	*p*-value
Beef cattle	α	1.5519	0.1521	< 0.001 (***)
	β	1.9993	0.3425	< 0.001 (***)
Dairy cattle	α	0.3987	0.0036	< 0.001 (***)
	β	0.6367	0.0143	< 0.001 (***)
Pigs	α	1.7334	0.3102	< 0.001 (***)
	β	1.3988	0.1103	< 0.001 (***)

Table S5. Statistical properties of weighted regression models for feed composition F_{comp}. Significance levels for *p*-values are denoted by (***): p < 0.001, (**): p ∈ [0.001, 0.01), (*): p ∈ [0.01, 0.05), (.): p ∈ [0.05, 0.1).

Animal food system	Intercept	Slope	R^2	*p*-value	F-statistics
Beef cattle	0.1289	0.8114	0.84	< 0.001 (***)	421
Dairy cattle	0.0902	0.8524	0.71	< 0.001 (***)	203
Pigs	0.2929	0.6035	0.67	< 0.001 (***)	162

A.4. Supplementary information on scenario assumptions

Socio-economic drivers are parametrized in line with the Shared Socioeconomic Pathways (SSPs) for climate change research (O'Neill et al., 2014; Popp et al., 2017). This study is following the narrative of SSP2, a „Middle of the Road" scenario with intermediate socio-economic challenges for adaptation and mitigation. Gross domestic product (GDP) and population trajectories of the SSP2 scenario reach global values of 230 trillion US Dollars (at 2005 prices and adjusted for purchasing power parity) and 9.1 billion people in 2050 (IIASA, 2013). The demand for food is regionally defined and given as an exogenous trend to the model, encompassing 16 crop categories and 5 livestock product groups. Regional projections of per capita food demand and the share of animal-based calories in diets are based on a country cross-section regression analysis on population and GDP (Bodirsky et al., 2015). The resulting average per capita food demand in 2050 amounts to 3174 kcal per day, with a contribution of 21% from animal-based calories (excluding fish). Material demand (including production waste) evolves proportionally with food demand. Regional feed demand is endogenously calculated depending on livestock production quantities, feed conversion F_C and feed baskets F_B (see section A.2). Regional processing rates link the generation of food industry byproducts to domestic supply of related crops. If projected feed demand for crop residues or food industry byproducts exceeds supply, alternative feedstock like food or forage crops of at least the same nutritional value is provided by the model, which induces additional land and water use. Global trade barriers for agricultural commodities are relaxed by 5% per decade, which is less than currently observed liberalization trends (Schmitz et al., 2012).

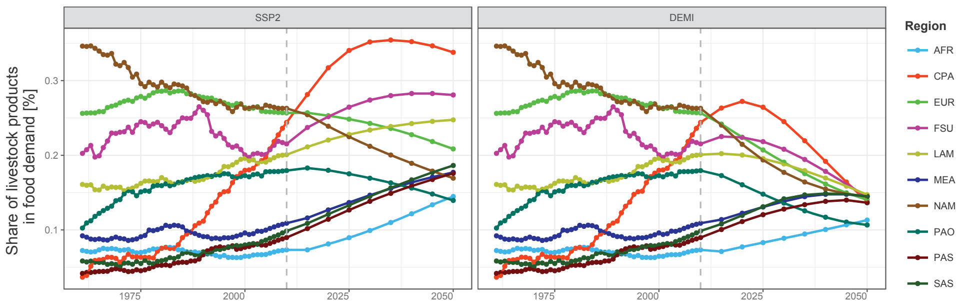


Fig. S7. Share of livestock products (excluding fish) in total calorie intake per person per day for all world regions. Historical development (left of the vertical dashed line) according to FAOSTAT (2013) and future developments (right of the vertical dashed line) for the two diet scenarios.

In order to assess demand- and supply-side potentials in the livestock sector to reduce agricultural water requirements and attenuate water scarcity, we explore six scenarios defined by assumptions on both dietary patterns and livestock productivity. In addition to the baseline diet scenario (SSP2), we consider an alternative development of dietary preferences (Fig. S7), which represents a gradual change of SSP2 diet projections to lower shares of animal-based calories in diets, with 15% as upper limit in 2050 for calories from livestock and fish. This scenario (DEMI) builds upon the concept of a "demitarian" Western diet in sustainability research (Sutton and Ayyappan, 2013), with the share of animal-based calories being approximately half the currently observed level in OECD countries. In some regions, projected intake of livestock products under the SSP2 scenario does not reach these levels and is therefore unaffected by reductions. Fig. S7 shows the temporal development of the contribution of livestock products to total calorie intake per person per day for all world regions and the two diet scenarios, including the historically observed development. Based on SSP2 diet projections, the DEMI diet scenario is determined as smooth convergence of SSP2 trajectories towards reduced shares of animal-based calories. The convergence process starts in 2010 and its smoothness ensures that both initial growth rates and the shape of the SSP2 projections are accounted for.

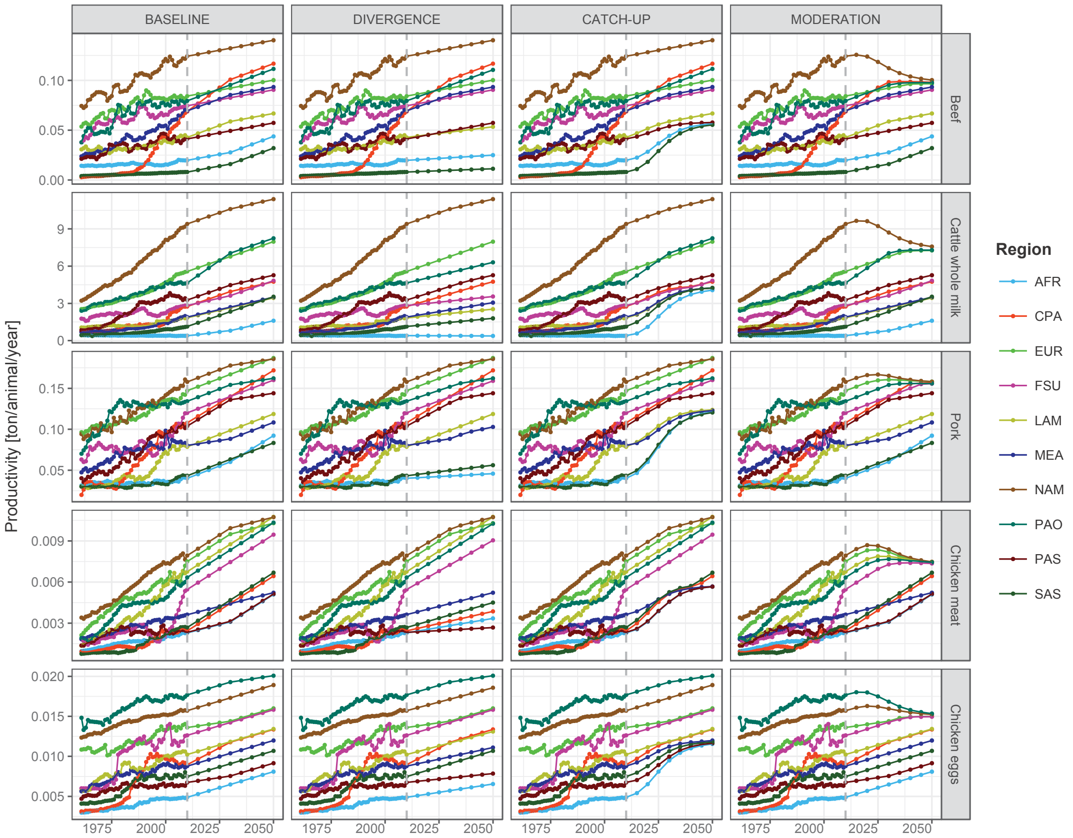


Fig. S8. Livestock productivity *P* (annual production per animal [ton/animal/year]) for all world regions and livestock products. Historical development (left of the vertical dashed line) according to FAOSTAT (2013) and future developments (right of the vertical dashed line) for the four productivity scenarios.

The two described diet scenarios are combined with four alternative assumptions on future livestock productivity. Fig. S8 illustrates the temporal development of regional livestock productivity *P* for all products and the four productivity scenarios. Livestock productivity for beef cattle, pigs and broilers is defined as meat production per animals in stock (i.e. total cattle herd) and for dairy cattle and laying hens as milk or egg production per producing animals (i.e. milk cows). The wide spread of historically very divergent developments between very low and highly productive regions motivates the construction of the three alternative productivity scenarios. The DIVERGENCE scenario represents the continuation of historically observed divergent trends. The ambitious CATCH-UP scenario assumes a further closure of the productivity gap, defined by top-performing countries in 2010, by 45% for ruminant systems and by 60% for monogastric systems until 2050. In the MODERATION scenario, highly intensive systems are assumed to experience a reduction in livestock productivity until 2050 to the level of 75% relative to the productivity frontier defined by top-performing countries in 2010.

Appendix B. Supplementary results

B.1. Regional feed baskets for all animal food systems in 2010

Table S6. Regional feed baskets F_B in 2010 for all animal food systems, expressed as units of feed used to generate one unit product on dry matter basis. Note that feed use includes energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals. For the dairy cattle system, product output comprises whole-milk as well as meat from milk cows (see Wirsenius (2000) for more information on herd structures).

Beef cattle	Food crops	Forage crops	Food industry byproducts	Crop residues	Permanent pasture & browse	Occasional feed & food waste	Total
AFR	1.4	3.3	2.3	27.1	230.1	0.0	264.1
CPA	6.2	29.6	0.0	17.3	72.1	0.0	125.1
EUR	3.4	22.4	6.6	3.1	48.8	0.0	84.2
FSU	13.0	36.8	2.7	1.4	31.9	0.0	85.8
LAM	0.4	12.7	0.0	15.7	136.6	0.0	165.4
MEA	12.7	26.0	8.2	10.7	44.5	0.0	102.0
NAM	9.2	28.4	4.5	1.4	18.0	0.0	61.5
PAO	1.2	29.7	2.1	0.7	69.5	0.0	103.1
PAS	0.9	2.5	0.8	47.6	128.1	0.0	179.9
SAS	0.9	4.0	4.7	92.7	152.7	152.7	407.7
Dairy cattle							
AFR	0.3	0.7	0.5	8.5	64.6	0.0	74.6
CPA	1.4	6.5	0.0	5.0	18.2	0.0	31.1
EUR	0.7	4.8	1.4	0.4	5.5	0.0	12.8
FSU	3.4	9.6	0.6	0.2	4.0	0.0	17.9
LAM	0.1	4.6	0.0	3.4	26.2	0.0	34.4
MEA	3.3	6.7	2.0	3.0	10.3	0.0	25.3
NAM	1.6	5.0	0.8	0.2	1.3	0.0	8.9
PAO	0.2	5.4	0.7	0.1	7.8	0.0	14.2
PAS	0.1	0.2	2.5	8.8	18.4	0.0	30.1
SAS	0.3	2.5	1.3	10.9	15.8	15.8	46.7
Pigs							
AFR	9.0	0.0	0.8	12.0	0.0	2.5	24.3
CPA	3.7	0.0	0.5	0.3	0.0	6.7	11.1
EUR	7.1	1.2	0.6	0.0	0.0	0.0	8.8
FSU	8.1	1.3	0.3	0.0	0.0	0.1	9.8
LAM	6.7	0.0	3.7	1.1	0.0	2.0	13.5
MEA	8.7	0.0	2.2	0.0	0.0	2.2	13.1
NAM	7.6	0.2	0.5	0.0	0.0	0.0	8.3
PAO	7.0	0.9	1.7	0.0	0.0	0.0	9.6
PAS	1.9	0.0	4.2	1.0	0.0	5.3	12.4
SAS	5.3	0.0	7.9	4.2	0.0	4.3	21.8
Broilers							
AFR	6.2	0.0	4.9	0.0	0.0	0.0	11.1
CPA	8.9	0.0	1.9	0.0	0.0	0.0	10.8
EUR	5.8	0.0	1.1	0.0	0.0	0.0	6.9
FSU	6.0	0.0	1.1	0.0	0.0	0.0	7.1
LAM	5.5	0.0	1.5	0.0	0.0	0.0	7.0
MEA	7.0	0.0	2.7	0.0	0.0	0.0	9.7
NAM	5.9	0.0	0.7	0.0	0.0	0.0	6.6
PAO	5.7	0.0	1.7	0.0	0.0	0.0	7.4
PAS	7.0	0.0	4.8	0.0	0.0	0.0	11.8
SAS	3.1	0.0	9.0	0.0	0.0	0.0	12.1
Laying hens							
AFR	6.9	0.0	5.5	0.0	0.0	0.0	12.4
CPA	7.7	0.0	1.7	0.0	0.0	0.0	9.3
EUR	6.2	0.0	1.2	0.0	0.0	0.0	7.4
FSU	6.6	0.0	1.2	0.0	0.0	0.0	7.8
LAM	6.6	0.0	1.7	0.0	0.0	0.0	8.3
MEA	6.8	0.0	2.7	0.0	0.0	0.0	9.5
NAM	5.6	0.0	0.7	0.0	0.0	0.0	6.4
PAO	5.2	0.0	1.5	0.0	0.0	0.0	6.8
PAS	6.4	0.0	4.4	0.0	0.0	0.0	10.8
SAS	3.0	0.0	8.8	0.0	0.0	0.0	11.8

B.2. Regional feed baskets in 2050 – BASELINE productivity scenario

Table S7. Regional feed baskets F_B in 2050 for all animal food systems for the BASELINE productivity scenario, expressed as units of feed used to generate one unit product on dry matter basis. Note that feed use includes energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals. For the dairy cattle system, product output comprises whole-milk as well as meat from milk cows (see Wirsenius (2000) for more information on herd structures).

	Food crops	Forage crops	Food industry byproducts	Crop residues	Permanent pasture & browse	Occasional feed & food waste	Total
Beef cattle							
AFR	4.4	10.4	7.3	14.2	120.4	0.0	156.6
CPA	9.0	42.9	0.0	7.0	29.2	0.0	88.1
EUR	3.8	24.6	7.3	2.3	36.9	0.0	74.8
FSU	13.8	39.0	2.8	0.8	18.6	0.0	75.1
LAM	1.0	30.3	0.0	9.5	82.4	0.0	123.2
MEA	14.7	29.9	9.5	5.7	23.9	0.0	83.7
NAM	9.3	28.5	4.5	1.0	13.5	0.0	56.8
PAO	1.5	38.5	2.7	0.4	39.5	0.0	82.6
PAS	3.0	8.0	2.4	35.2	94.8	0.0	143.4
SAS	1.3	5.6	6.5	35.4	58.3	58.3	165.2
Dairy cattle							
AFR	1.4	3.2	2.3	4.0	30.5	0.0	41.4
CPA	1.8	8.8	0.0	3.0	11.0	0.0	24.6
EUR	0.8	5.5	1.5	0.2	3.0	0.0	11.0
FSU	3.2	9.3	0.6	0.1	1.0	0.0	14.2
LAM	0.3	8.1	0.0	2.1	15.9	0.0	26.3
MEA	3.8	7.8	2.4	1.2	4.2	0.0	19.5
NAM	1.6	4.9	0.8	0.1	0.8	0.0	8.2
PAO	0.3	6.8	0.9	0.0	3.1	0.0	11.1
PAS	0.2	0.6	6.4	5.6	11.7	0.0	24.5
SAS	0.8	7.2	3.8	4.8	6.9	6.9	30.5
Pigs							
AFR	7.1	0.0	0.4	6.1	0.0	1.2	14.8
CPA	5.1	0.0	0.2	0.1	0.0	3.0	8.4
EUR	6.6	0.7	0.3	0.0	0.0	0.0	7.7
FSU	7.4	0.7	0.2	0.0	0.0	0.0	8.2
LAM	6.5	0.0	2.2	0.7	0.0	1.2	10.6
MEA	7.8	0.0	1.6	0.0	0.0	1.6	11.0
NAM	7.0	0.1	0.4	0.0	0.0	0.0	7.5
PAO	6.7	0.6	1.2	0.0	0.0	0.0	8.5
PAS	3.8	0.0	2.5	0.6	0.0	3.3	10.2
SAS	4.6	0.0	4.9	2.6	0.0	2.7	14.7
Broilers							
AFR	4.0	0.0	3.2	0.0	0.0	0.0	7.3
CPA	5.3	0.0	1.2	0.0	0.0	0.0	6.5
EUR	4.9	0.0	0.9	0.0	0.0	0.0	5.8
FSU	4.5	0.0	0.8	0.0	0.0	0.0	5.3
LAM	4.3	0.0	1.1	0.0	0.0	0.0	5.4
MEA	5.8	0.0	2.3	0.0	0.0	0.0	8.0
NAM	5.0	0.0	0.6	0.0	0.0	0.0	5.6
PAO	4.4	0.0	1.3	0.0	0.0	0.0	5.7
PAS	4.6	0.0	3.2	0.0	0.0	0.0	7.8
SAS	1.9	0.0	5.6	0.0	0.0	0.0	7.5
Laying hens							
AFR	5.1	0.0	4.1	0.0	0.0	0.0	9.2
CPA	6.0	0.0	1.3	0.0	0.0	0.0	7.4
EUR	5.6	0.0	1.1	0.0	0.0	0.0	6.7
FSU	5.7	0.0	1.0	0.0	0.0	0.0	6.8
LAM	5.6	0.0	1.5	0.0	0.0	0.0	7.1
MEA	5.7	0.0	2.2	0.0	0.0	0.0	7.9
NAM	5.1	0.0	0.7	0.0	0.0	0.0	5.7
PAO	4.9	0.0	1.4	0.0	0.0	0.0	6.3
PAS	5.3	0.0	3.7	0.0	0.0	0.0	9.0
SAS	2.4	0.0	7.1	0.0	0.0	0.0	9.6

B.3. Regional feed baskets in 2050 - DIVERGENCE productivity scenario

Table S8. Regional feed baskets F_B in 2050 for all animal food systems for the DIVERGENCE productivity scenario, expressed as units of feed used to generate one unit product on dry matter basis. Note that feed use includes energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals. For the dairy cattle system, product output comprises whole-milk as well as meat from milk cows (see Wirsenius (2000) for more information on herd structures).

	Food crops	Forage crops	Food industry byproducts	Crop residues	Permanent pasture & browse	Occasional feed & food waste	Total
Beef cattle							
AFR	1.9	4.4	3.1	22.8	194.1	0.0	226.3
CPA	9.0	42.9	0.0	7.0	29.2	0.0	88.1
EUR	3.8	24.6	7.3	2.3	36.9	0.0	74.8
FSU	13.8	39.0	2.8	0.8	18.6	0.0	75.1
LAM	0.7	21.5	0.0	12.4	108.1	0.0	142.7
MEA	14.7	29.9	9.5	5.7	23.9	0.0	83.7
NAM	9.3	28.5	4.5	1.0	13.5	0.0	56.8
PAO	1.5	38.3	2.7	0.4	40.2	0.0	83.1
PAS	3.0	8.0	2.4	35.2	94.8	0.0	143.4
SAS	0.8	3.5	4.0	73.9	121.7	121.7	325.6
Dairy cattle							
AFR	0.3	0.7	0.5	8.7	66.3	0.0	76.5
CPA	1.8	8.8	0.0	3.0	11.0	0.0	24.6
EUR	0.8	5.5	1.5	0.2	3.0	0.0	11.0
FSU	3.4	9.8	0.7	0.1	2.2	0.0	16.2
LAM	0.2	6.7	0.0	2.6	20.4	0.0	30.0
MEA	3.8	7.8	2.4	1.5	5.1	0.0	20.6
NAM	1.6	4.9	0.8	0.1	0.8	0.0	8.2
PAO	0.3	6.2	0.8	0.1	5.2	0.0	12.5
PAS	0.2	0.6	6.4	5.6	11.7	0.0	24.5
SAS	0.5	4.7	2.5	8.1	11.7	11.7	39.2
Pigs							
AFR	8.5	0.0	0.7	11.0	0.0	2.3	22.5
CPA	5.1	0.0	0.2	0.1	0.0	3.0	8.4
EUR	6.6	0.7	0.3	0.0	0.0	0.0	7.7
FSU	7.4	0.7	0.2	0.0	0.0	0.0	8.3
LAM	6.5	0.0	2.2	0.7	0.0	1.2	10.6
MEA	8.0	0.0	1.7	0.0	0.0	1.7	11.3
NAM	7.0	0.1	0.4	0.0	0.0	0.0	7.5
PAO	6.7	0.6	1.2	0.0	0.0	0.0	8.5
PAS	3.8	0.0	2.5	0.6	0.0	3.3	10.2
SAS	4.8	0.0	6.7	3.5	0.0	3.6	18.6
Broilers							
AFR	5.0	0.0	4.0	0.0	0.0	0.0	9.1
CPA	7.0	0.0	1.5	0.0	0.0	0.0	8.5
EUR	4.9	0.0	0.9	0.0	0.0	0.0	5.8
FSU	4.6	0.0	0.8	0.0	0.0	0.0	5.4
LAM	4.3	0.0	1.1	0.0	0.0	0.0	5.4
MEA	5.8	0.0	2.3	0.0	0.0	0.0	8.0
NAM	5.0	0.0	0.6	0.0	0.0	0.0	5.6
PAO	4.4	0.0	1.3	0.0	0.0	0.0	5.7
PAS	6.5	0.0	4.5	0.0	0.0	0.0	11.0
SAS	2.3	0.0	6.8	0.0	0.0	0.0	9.2
Laying hens							
AFR	5.8	0.0	4.6	0.0	0.0	0.0	10.4
CPA	6.0	0.0	1.3	0.0	0.0	0.0	7.4
EUR	5.6	0.0	1.1	0.0	0.0	0.0	6.7
FSU	5.7	0.0	1.0	0.0	0.0	0.0	6.8
LAM	5.7	0.0	1.5	0.0	0.0	0.0	7.2
MEA	6.0	0.0	2.3	0.0	0.0	0.0	8.3
NAM	5.1	0.0	0.7	0.0	0.0	0.0	5.8
PAO	4.9	0.0	1.4	0.0	0.0	0.0	6.3
PAS	5.8	0.0	4.0	0.0	0.0	0.0	9.9
SAS	2.4	0.0	7.1	0.0	0.0	0.0	9.6

B.4. Regional feed baskets in 2050 – CATCH-UP productivity scenario

Table S9. Regional feed baskets F_B in 2050 for all animal food systems for the CATCH-UP productivity scenario, expressed as units of feed used to generate one unit product on dry matter basis. Note that feed use includes energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals. For the dairy cattle system, product output comprises whole-milk as well as meat from milk cows (see Wirsenius (2000) for more information on herd structures).

	Food crops	Forage crops	Food industry byproducts	Crop residues	Permanent pasture & browse	Occasional feed & food waste	Total
Beef cattle							
AFR	6.1	14.4	10.1	10.7	91.0	0.0	132.3
CPA	9.0	42.9	0.0	7.0	29.2	0.0	88.1
EUR	3.8	24.6	7.3	2.3	36.9	0.0	74.8
FSU	13.8	39.0	2.8	0.8	18.6	0.0	75.1
LAM	1.0	30.3	0.0	9.5	82.4	0.0	123.2
MEA	14.7	29.9	9.5	5.7	23.9	0.0	83.7
NAM	9.3	28.5	4.5	1.0	13.5	0.0	56.8
PAO	1.5	38.5	2.7	0.4	39.5	0.0	82.6
PAS	3.1	8.1	2.5	34.9	94.1	0.0	142.7
SAS	2.6	11.2	12.9	21.0	34.6	34.6	117.1
Dairy cattle							
AFR	2.4	5.6	3.9	1.8	14.0	0.0	27.8
CPA	1.8	8.8	0.0	3.0	11.0	0.0	24.6
EUR	0.8	5.5	1.5	0.2	3.0	0.0	11.0
FSU	3.2	9.3	0.6	0.1	1.0	0.0	14.2
LAM	0.3	9.0	0.0	1.7	13.1	0.0	24.1
MEA	3.8	7.7	2.3	0.9	3.2	0.0	18.0
NAM	1.6	4.9	0.8	0.1	0.8	0.0	8.2
PAO	0.3	6.8	0.9	0.0	3.1	0.0	11.1
PAS	0.2	0.6	6.4	5.6	11.7	0.0	24.5
SAS	0.8	7.7	4.1	4.1	5.9	5.9	28.5
Pigs							
AFR	7.1	0.0	0.3	4.3	0.0	0.9	12.6
CPA	5.1	0.0	0.2	0.1	0.0	3.0	8.4
EUR	6.6	0.7	0.3	0.0	0.0	0.0	7.7
FSU	7.4	0.7	0.2	0.0	0.0	0.0	8.2
LAM	6.5	0.0	2.1	0.6	0.0	1.2	10.3
MEA	7.6	0.0	1.3	0.0	0.0	1.3	10.2
NAM	7.0	0.1	0.4	0.0	0.0	0.0	7.5
PAO	6.7	0.6	1.2	0.0	0.0	0.0	8.5
PAS	3.8	0.0	2.5	0.6	0.0	3.3	10.2
SAS	5.2	0.0	3.2	1.7	0.0	1.7	11.8
Broilers							
AFR	3.8	0.0	3.1	0.0	0.0	0.0	6.9
CPA	5.3	0.0	1.2	0.0	0.0	0.0	6.5
EUR	4.9	0.0	0.9	0.0	0.0	0.0	5.8
FSU	4.5	0.0	0.8	0.0	0.0	0.0	5.3
LAM	4.3	0.0	1.1	0.0	0.0	0.0	5.4
MEA	5.5	0.0	2.2	0.0	0.0	0.0	7.7
NAM	5.0	0.0	0.6	0.0	0.0	0.0	5.6
PAO	4.4	0.0	1.3	0.0	0.0	0.0	5.7
PAS	4.4	0.0	3.0	0.0	0.0	0.0	7.4
SAS	1.9	0.0	5.6	0.0	0.0	0.0	7.5
Laying hens							
AFR	4.1	0.0	3.3	0.0	0.0	0.0	7.4
CPA	6.0	0.0	1.3	0.0	0.0	0.0	7.4
EUR	5.6	0.0	1.1	0.0	0.0	0.0	6.7
FSU	5.7	0.0	1.0	0.0	0.0	0.0	6.8
LAM	5.6	0.0	1.5	0.0	0.0	0.0	7.1
MEA	5.7	0.0	2.2	0.0	0.0	0.0	7.9
NAM	5.1	0.0	0.7	0.0	0.0	0.0	5.7
PAO	4.9	0.0	1.4	0.0	0.0	0.0	6.3
PAS	4.6	0.0	3.2	0.0	0.0	0.0	7.8
SAS	2.3	0.0	6.7	0.0	0.0	0.0	9.0

B.5. Regional feed baskets in 2050 - MODERATION productivity scenario

Table S10. Regional feed baskets F_B in 2050 for all animal food systems for the MODERATION productivity scenario, expressed as units of feed used to generate one unit product on dry matter basis. Note that feed use includes energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals. For the dairy cattle system, product output comprises whole-milk as well as meat from milk cows (see Wirsenius (2000) for more information on herd structures).

Beef cattle	Food crops	Forage crops	Food industry byproducts	Crop residues	Permanent pasture & browse	Occasional feed & food waste	Total
AFR	4.4	10.4	7.3	14.2	120.4	0.0	156.6
CPA	8.3	39.5	0.0	9.9	41.2	0.0	98.9
EUR	3.7	24.1	7.2	2.5	39.3	0.0	76.8
FSU	13.8	39.0	2.8	0.8	18.6	0.0	75.1
LAM	1.0	30.3	0.0	9.5	82.4	0.0	123.2
MEA	14.7	29.9	9.5	5.7	23.9	0.0	83.7
NAM	8.9	27.3	4.3	2.2	28.1	0.0	70.8
PAO	1.4	35.2	2.4	0.5	50.5	0.0	90.1
PAS	3.0	8.0	2.4	35.2	94.8	0.0	143.4
SAS	1.3	5.6	6.5	35.4	58.3	58.3	165.2
Dairy cattle							
AFR	1.4	3.2	2.3	4.0	30.5	0.0	41.4
CPA	1.8	8.8	0.0	3.0	11.0	0.0	24.6
EUR	0.8	5.3	1.5	0.3	3.6	0.0	11.4
FSU	3.2	9.3	0.6	0.1	1.0	0.0	14.2
LAM	0.3	8.1	0.0	2.1	15.9	0.0	26.3
MEA	3.8	7.8	2.4	1.2	4.2	0.0	19.5
NAM	1.6	5.0	0.8	0.3	2.1	0.0	9.8
PAO	0.3	6.5	0.8	0.1	4.0	0.0	11.7
PAS	0.2	0.6	6.4	5.6	11.7	0.0	24.5
SAS	0.8	7.2	3.8	4.8	6.9	6.9	30.5
Pigs							
AFR	7.1	0.0	0.4	6.1	0.0	1.2	14.8
CPA	4.9	0.0	0.3	0.1	0.0	3.6	8.9
EUR	7.0	1.0	0.5	0.0	0.0	0.0	8.5
FSU	7.5	0.7	0.2	0.0	0.0	0.0	8.4
LAM	6.5	0.0	2.2	0.7	0.0	1.2	10.6
MEA	7.8	0.0	1.6	0.0	0.0	1.6	11.0
NAM	7.6	0.2	0.5	0.0	0.0	0.0	8.3
PAO	6.8	0.7	1.3	0.0	0.0	0.0	8.7
PAS	3.8	0.0	2.5	0.6	0.0	3.3	10.2
SAS	4.6	0.0	4.9	2.6	0.0	2.7	14.7
Broilers							
AFR	4.0	0.0	3.2	0.0	0.0	0.0	7.3
CPA	5.3	0.0	1.2	0.0	0.0	0.0	6.5
EUR	5.8	0.0	1.1	0.0	0.0	0.0	6.9
FSU	5.1	0.0	0.9	0.0	0.0	0.0	6.0
LAM	5.2	0.0	1.4	0.0	0.0	0.0	6.6
MEA	5.8	0.0	2.3	0.0	0.0	0.0	8.0
NAM	6.1	0.0	0.8	0.0	0.0	0.0	6.8
PAO	5.2	0.0	1.5	0.0	0.0	0.0	6.8
PAS	4.6	0.0	3.2	0.0	0.0	0.0	7.8
SAS	1.9	0.0	5.6	0.0	0.0	0.0	7.5
Laying hens							
AFR	5.1	0.0	4.1	0.0	0.0	0.0	9.2
CPA	6.0	0.0	1.3	0.0	0.0	0.0	7.4
EUR	5.9	0.0	1.1	0.0	0.0	0.0	7.0
FSU	5.9	0.0	1.1	0.0	0.0	0.0	7.0
LAM	5.6	0.0	1.5	0.0	0.0	0.0	7.1
MEA	5.7	0.0	2.2	0.0	0.0	0.0	7.9
NAM	5.7	0.0	0.7	0.0	0.0	0.0	6.5
PAO	5.7	0.0	1.7	0.0	0.0	0.0	7.4
PAS	5.3	0.0	3.7	0.0	0.0	0.0	9.0
SAS	2.4	0.0	7.1	0.0	0.0	0.0	9.6

B.6. Global green (G) and blue (B) water consumption attributable to the agricultural and the livestock sector in 2050

Table S11. Global green (G) and blue (B) water consumption attributable to total agriculture and the livestock sector in 2050 for all scenarios and in the reference year 2010 in km^3yr^{-1}. G on cropland is differentiated according to rainfed (G_{rf}) and irrigated cropland (Gi_{rr}). On pastures, G is differentiated between evapotranspiration on total pasture area (G_{past_area}) and G attributable to grazed biomass (G_{past_feed}), the residuum being interpreted as sustaining ecosystem services (G_{past_ecosys}).

		SSP2 (2050)				DEMI (2050)			
	2010	BASELINE	DIVERGENCE	CATCH-UP	MODERATION	BASELINE	DIVERGENCE	CATCH-UP	MODERATION
Total agriculture									
B	1020	1330	1260	1390	1310	1310	1210	1330	1330
G_{irr}	790	1490	1440	1500	1440	1230	1230	1280	1260
G_{rf}	5250	7960	7100	8680	8070	7250	6370	7720	7150
G	6040	9440	8540	10180	9510	8490	7610	9000	8410
$G + B$	7070	10770	9800	11570	10820	9800	8820	10330	9730
$G_{past\ feed}$	2930	3080	4330	2640	3360	2310	3170	1720	2380
$G_{past\ ecosys}$	13500	12390	14660	11780	12270	12650	13680	12650	12630
$G_{past\ area}$	16430	15470	18990	14420	15630	14960	16840	14370	15010
$G + B + G_{past\ feed}$	9990	13860	14140	14210	14180	12110	11980	12050	12120
$G + B + G_{past\ area}$	23500	26250	28790	26000	26450	24760	25660	24700	24740
Livestock only									
B	370	560	530	560	550	450	410	440	460
G_{irr}	330	640	660	630	610	400	430	420	410
G_{rf}	1960	3330	2880	3730	3420	2430	1980	2660	2360
G	2290	3980	3540	4360	4030	2830	2410	3080	2770
$G + B$	2670	4540	4070	4930	4570	3280	2820	3520	3230
$G + B + G_{past\ feed}$	5590	7630	8400	7570	7930	5590	5980	5240	5620
$G + B + G_{past\ area}$	19100	20020	23060	19350	20210	18240	19660	17890	18240

B.7. Regional demand trajectories between 1995 and 2050

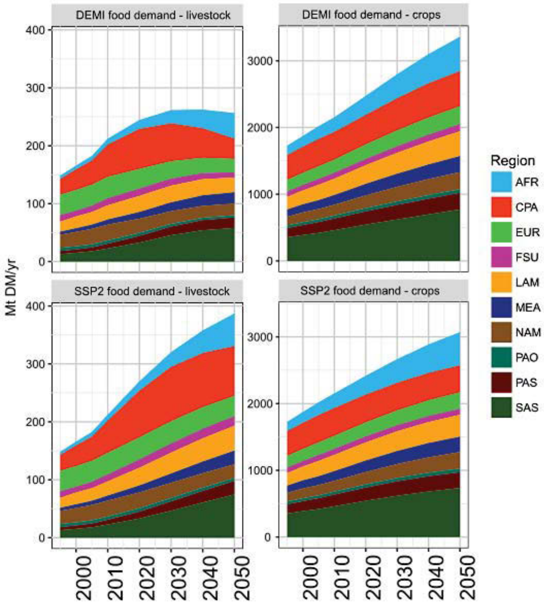


Fig. S9. Regional food demand trajectories for livestock products (left panels) and crops (right panel) between 1995 and 2050. Lower panels depict food demand projections for the SSP2 diet scenario which is calculated based on SSP2 projections on population and income trends following the methodology from Bodirsky et al. (2015). Upper panels illustrate food demand projections for the DEMI diet scenario where the share of animal-based calories (including fish) in diets is assumed to decrease in affluent regions, reaching a maximum of 15% until 2050.

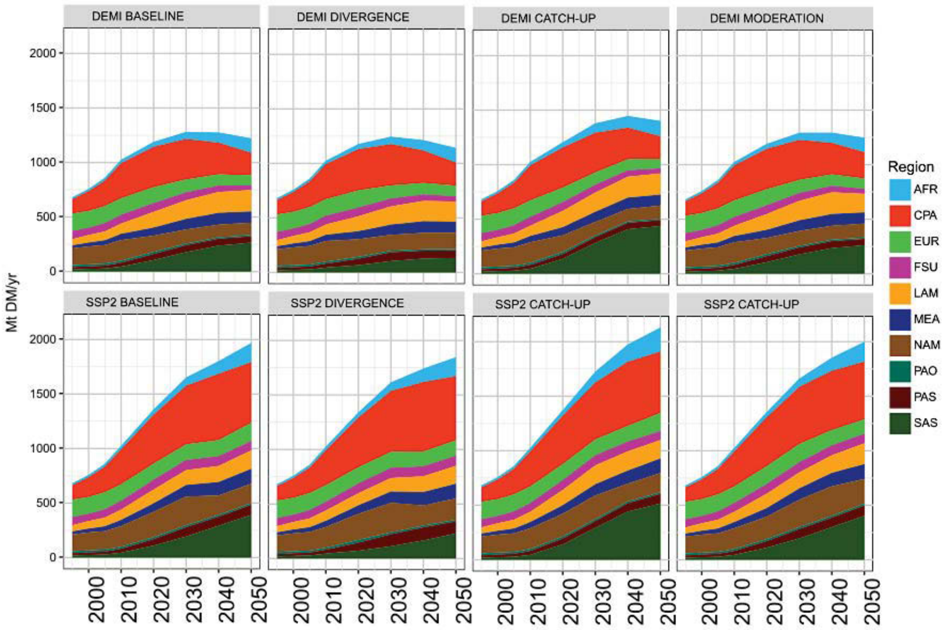


Fig. S10. Regional feed demand trajectories for food crops between 1995 and 2050 for all diet and productivity scenarios. Lower panels depict feed demand projections for the SSP2 diet scenario, which are endogenously calculated based on regional livestock production and animal system-specific feed baskets that depend on livestock productivity assumptions. Upper panels illustrate feed demand projections for the DEMI diet scenario.

B.8. Regional projections of agricultural production between 1995 and 2050

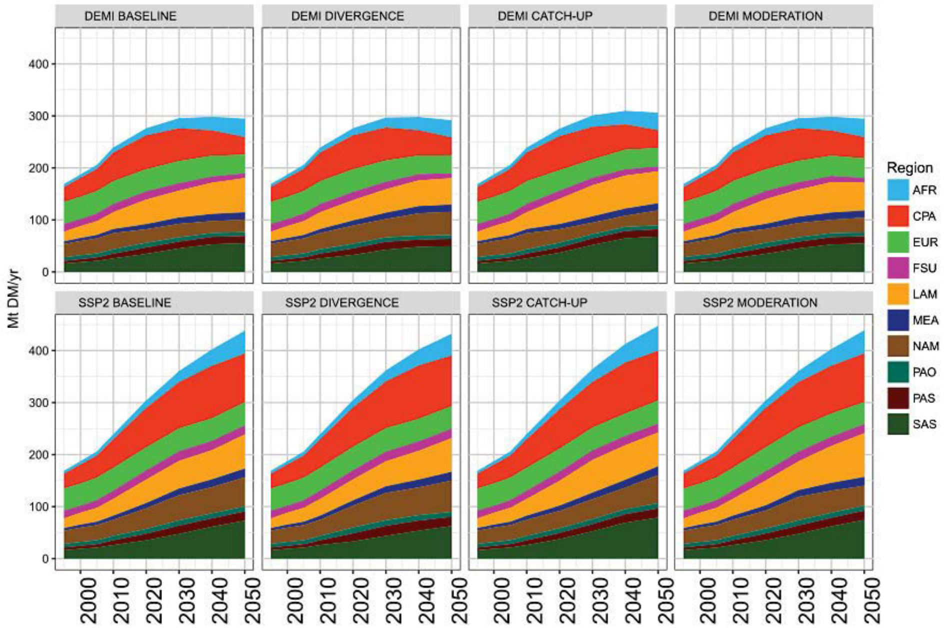


Fig. S11. Regional livestock production between 1995 and 2050 for all diet and productivity scenarios. Lower panels depict regional developments of livestock production for the SSP2 diet scenario and upper panels illustrate regional trends for the DEMI diet scenario. Since livestock productivity assumptions affect comparative advantages between regions, regional livestock production is influenced by productivity scenarios.

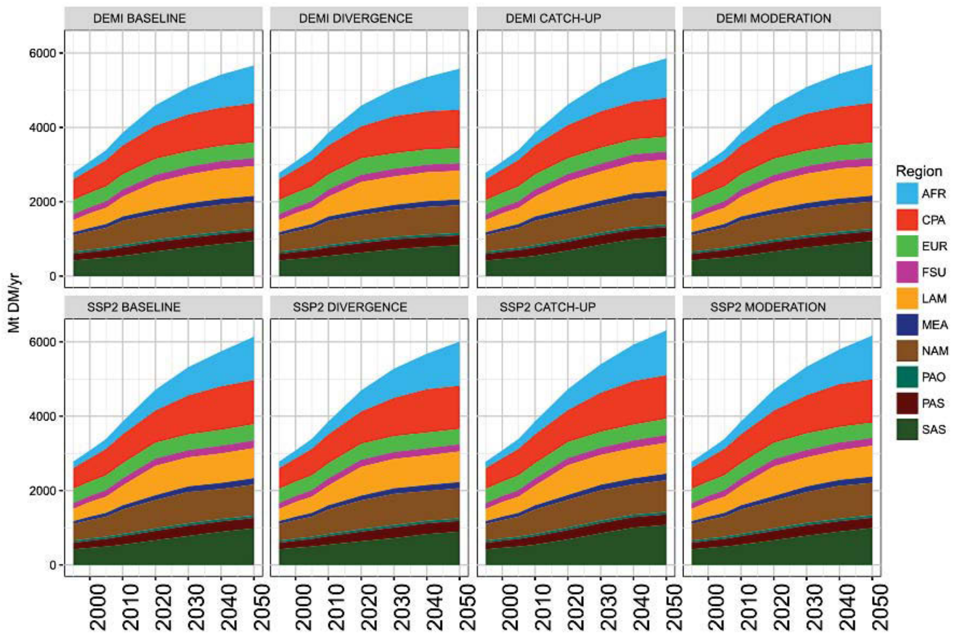


Fig. S12. Regional production of food crops between 1995 and 2050 for all diet and productivity scenarios. Lower panels depict regional development of food crop production for the SSP2 diet scenario and upper panels illustrate regional trends for the DEMI diet scenario. Since livestock productivity assumptions affect the magnitude of regional feed demand for food crops, regional food crop production is influenced by productivity scenarios.

B.9. Changes in agricultural water consumption between 2010 and 2050

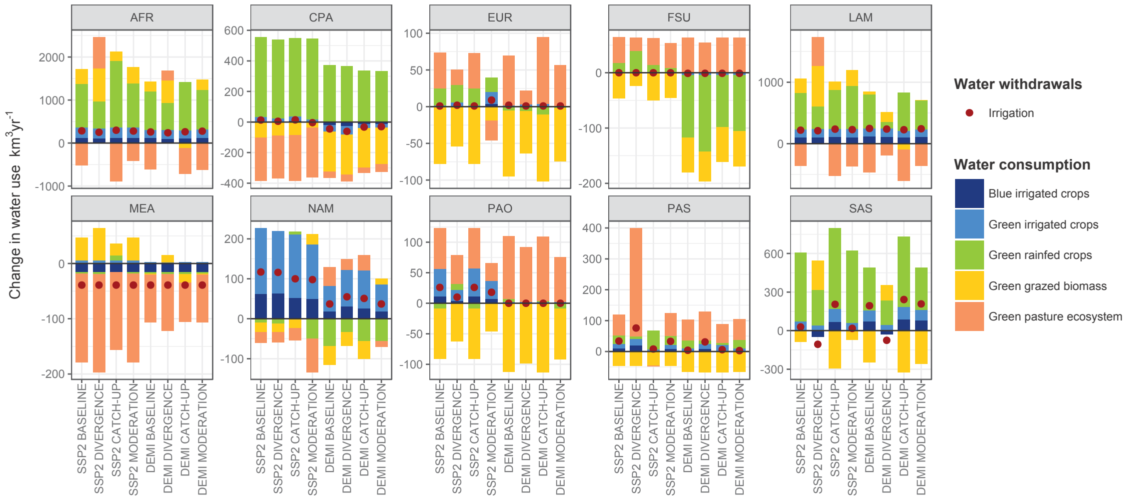


Fig. S13. Changes in regional agricultural green (G) and blue (B) water consumption between 2010 and 2050 in km^3yr^{-1}, including water consumption attributable to non-harvested biomass on pastures which sustains ecosystem functioning. Red points indicate changes in regional water withdrawals for irrigation (Wd_{irr}) between 2010 and 2050 in km^3yr^{-1}.

B.10. Agricultural and total water withdrawal-to-availability ratio (WTA) for the SSP2-TREND scenario and the years 2010 and 2050

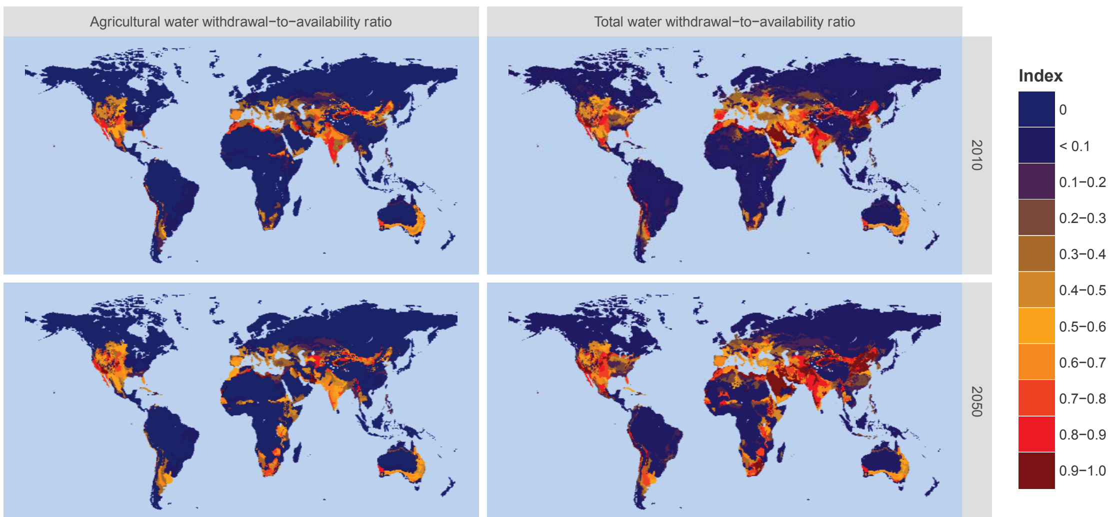


Fig. S14. Global distribution of the agricultural and total water withdrawal-to-availability ratio (WTA) for the SSP2 BASELINE scenario and the years 2010 and 2050. The total WTA ratio is calculated as $WTA=Wd/RFWR$, where Wd represents water withdrawals from all sectors and RFWR denotes renewable freshwater resources. The agricultural WTA ratio is calculated as $WTA=Wd_{irr}/RFWR$, where Wd_{irr} represents water withdrawals for irrigation.

B.11. Regional assessment of water scarcity

Fig. S15. Regional cropland under progressive levels of water stress in million ha, derived by aggregating cropland area of concordant WTA classes from simulation units to model regions. The length of each bar represents total regional cropland. The first bar in each panel indicates values for the reference year 2010. Scenario results are given for 2050.

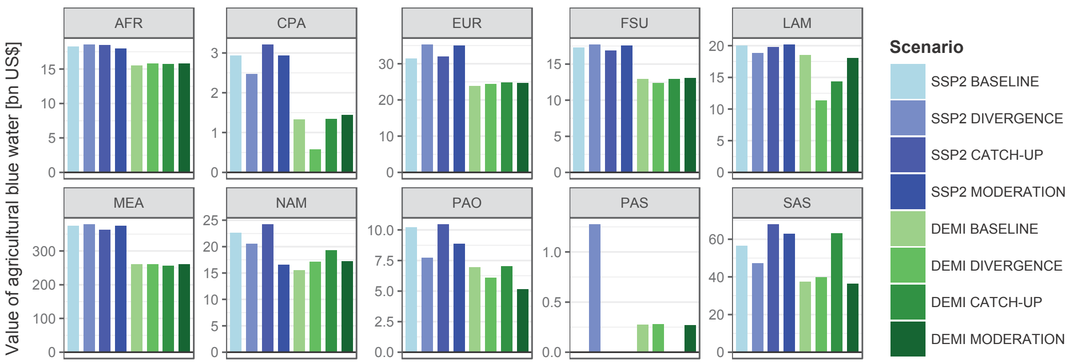


Fig. S16. Regional economic value of annual water withdrawals for irrigation in 2050 in billion US$, which facilitates a combined regional assessment of the sensitivity of *WSP* and Wd_{irr} to scenario assumptions. It is derived by multiplying *WSP* and Wd_{irr} at the level of simulation units and aggregating spatially explicit estimates to regions. Note that scales vary for the y-axes between regions.

B.12. Average yield increases (2010 – 2050) and livestock densities in 2050

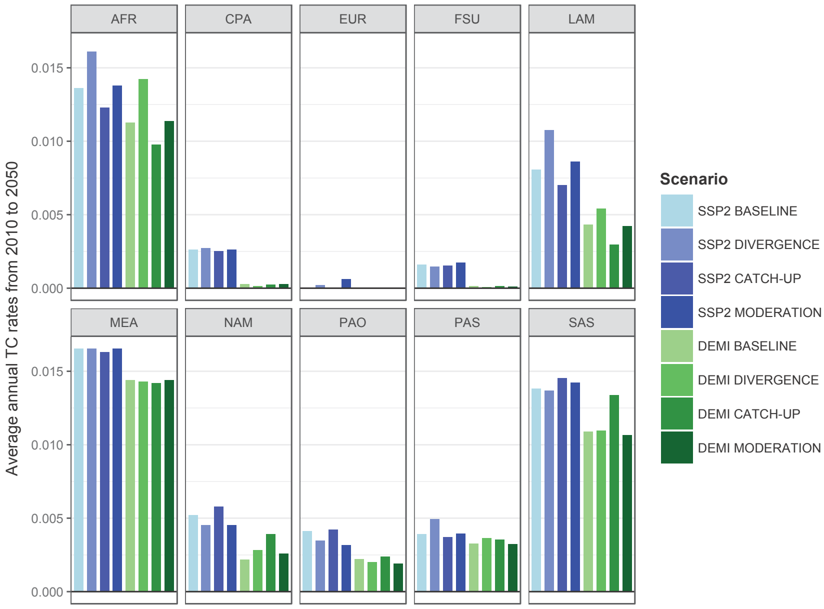


Fig. S17. Regional average annual rates of technological change (TC) from 2010 to 2050 for all scenarios. TC rates are equivalent with associated yield increases (see Dietrich et al. (2014) for more information with regard to the relationship between TC investments and induced yield growth).

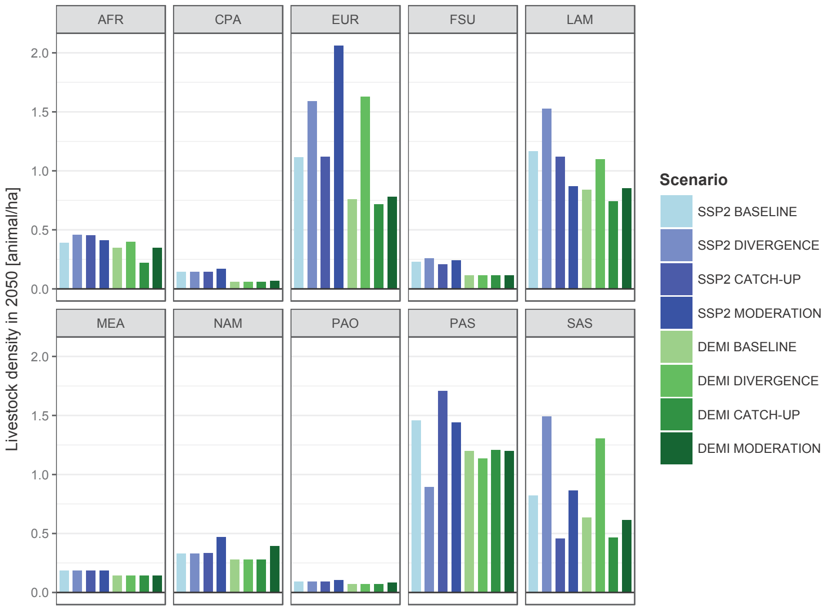


Fig. S18. Regional livestock densities in 2050 for all scenarios. Livestock density is defined as number of cattle per ha pasture for all regions (except SAS, where it is calculated as number of cattle per ha agricultural land due to the large contribution of crop residues and occasional feed to cattle feed baskets; see Wirsenius (2000) for a detailed discussion of the livestock sector in SAS).

B.13. Net trade flows between 2010 and 2050

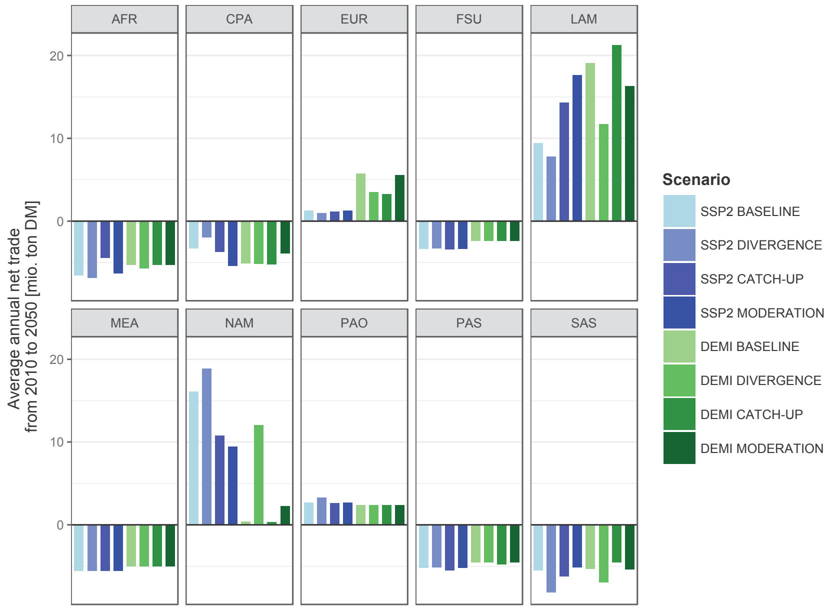


Fig. S19. Regional annual net trade of livestock products (average over the period 2010 -2050) for all scenarios in million tons dry matter. Positive values indicate net-exports, negative values net-imports.

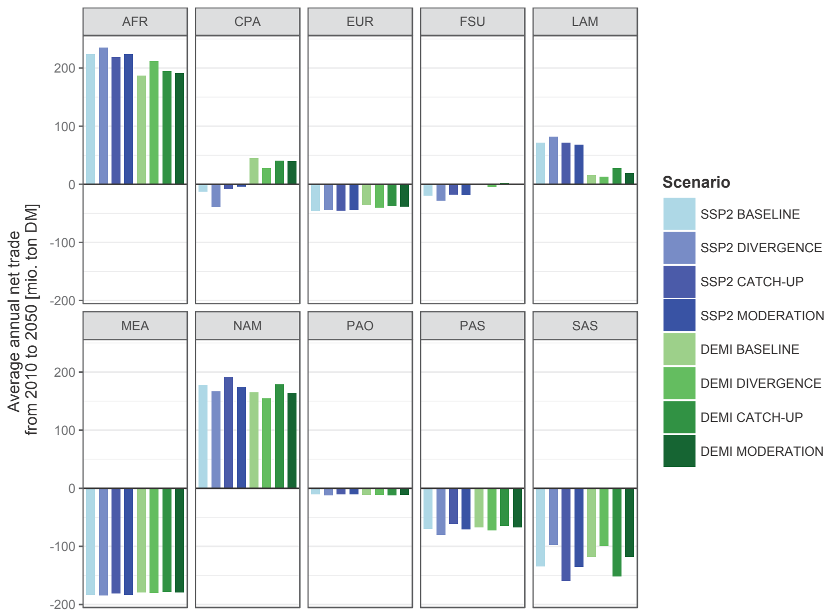


Fig. S20. Regional annual net trade of crop products (average over the period 2010 -2050) for all scenarios in million tons dry matter. Positive values indicate net-exports, negative values net-imports.

B.14. Regional development of cropland and pasture

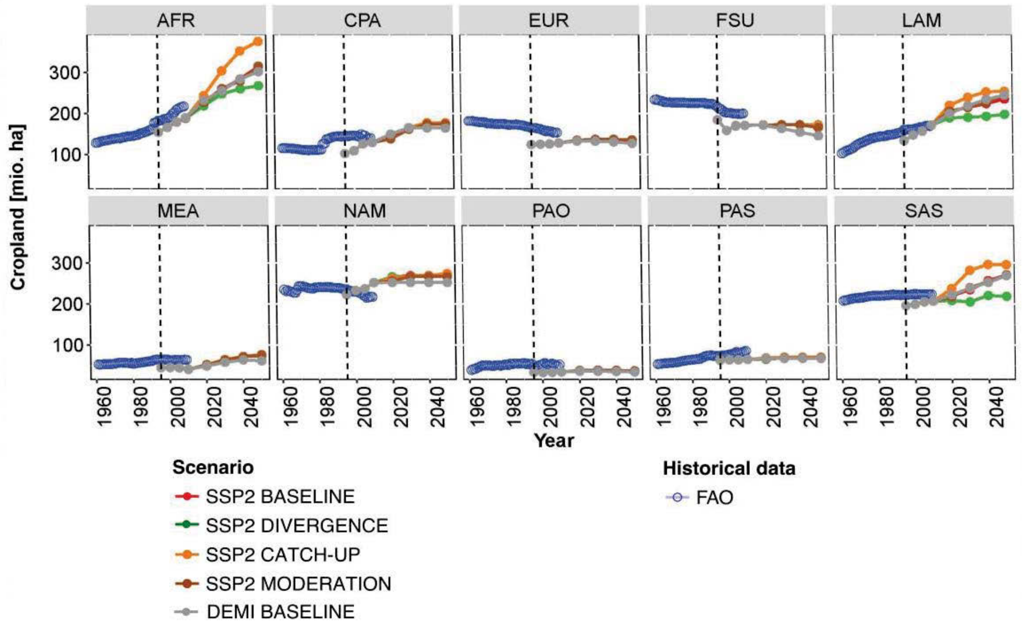


Fig. S21. Regional cropland development under four scenarios. Estimates of historical cropland by FAOSTAT (2013) (FAO, blue) for comparison. A vertical dashed line indicates the start of the simulation period.

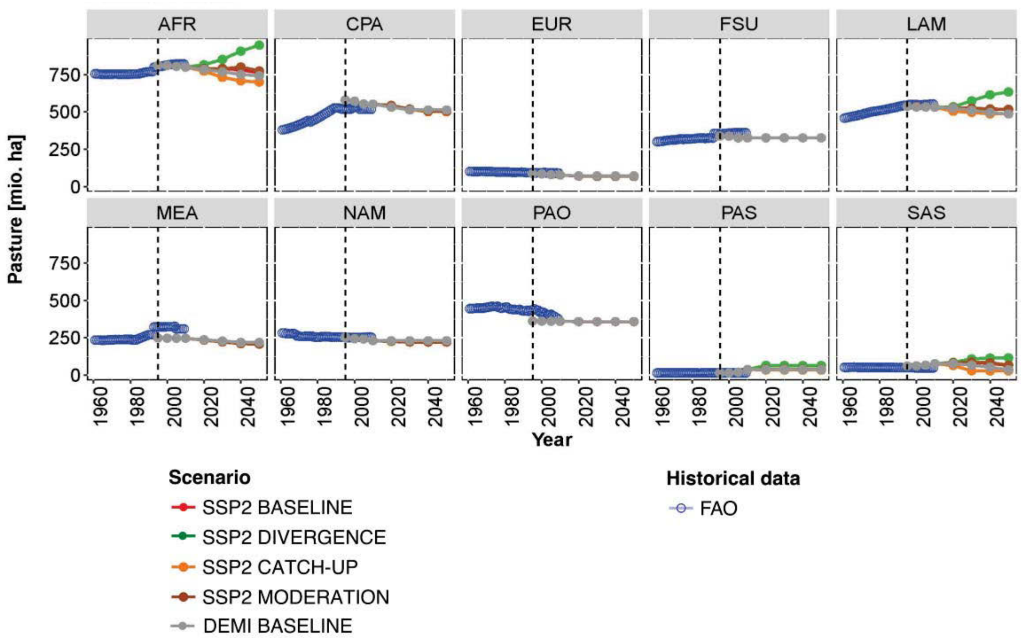


Fig. S22. Regional pasture development under four scenarios. Estimates of historical pasture by FAOSTAT (2013) (FAO, blue) for comparison. A vertical dashed line indicates the start of the simulation period.

B.15. Development of land-use intensity

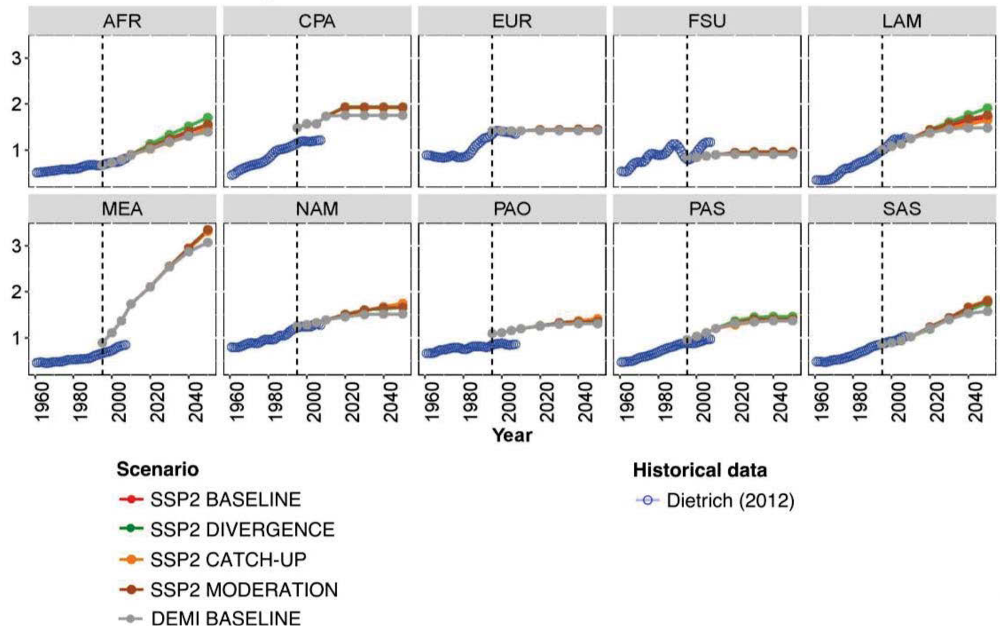


Fig. S23. Regional development of land-use intensity under four scenarios. Increases of land-use intensity are proportional to yield increases. Methodology and historical data from Dietrich et al. (2012) (see also Dietrich et al. (2014) for more information on the endogenous implementation of technological change in MAgPIE). A vertical dashed line indicates the start of the simulation period.

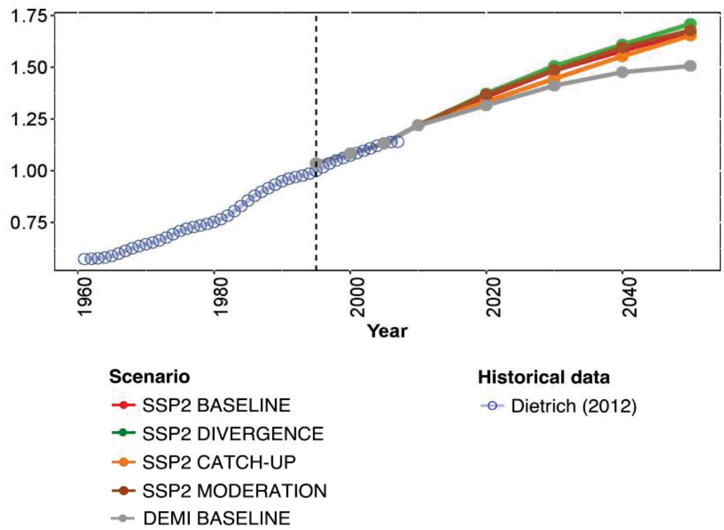


Fig. S24. Global development of land-use intensity under four scenarios. Increases of land-use intensity are proportional to yield increases. Methodology and historical data from Dietrich et al. (2012) (see also Dietrich et al. (2014) for more information on the endogenous implementation of technological change in MAgPIE). A vertical dashed line indicates the start of the simulation period.

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Chapter V: Livestock and human use of land: productivity trends and dietary choices as drivers of future land and carbon dynamics

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Contents

Livestock and human use of land: productivity trends and dietary choices as drivers of future land and carbon dynamics

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Abstract. Land use change has been the primary driving force of human alteration of terrestrial ecosystems. With 80% of agricultural land dedicated to livestock production, the sector is an important lever to attenuate land requirements for food production and carbon emissions from land use change. In this study, we quantify impacts of changing human diets and livestock productivity on land dynamics and depletion of carbon stored in vegetation, litter and soils. Across all investigated productivity pathways, lower consumption of livestock products can substantially reduce deforestation (47-55%) and cumulative carbon losses (34-57%). On the supply side, already minor productivity growth in extensive livestock production systems leads to substantial CO_2 emission abatement, but the emission saving potential of productivity gains in intensive systems is limited, mainly due to trade-offs with soil carbon stocks. If also accounting for uncertainties related to future trade restrictions, crop yields and pasture productivity, the range of projected carbon savings from changing diets increases to 23-78%. Highest abatement of carbon emissions (63-78%) can be achieved if reduced consumption of animal-based products is combined with sustained investments into productivity increases in plant production. Our analysis emphasizes the importance to integrate demand- and supply-side oriented mitigation strategies and to combine efforts in the crop and livestock sector to enable synergies for climate protection.

Keywords: livestock productivity; diets; land use; deforestation; carbon emissions; greenhouse gas mitigation

1. Introduction

Land is a fundamental resource for human societies not only for generating vital products like food, feed, fibre, wood and other raw materials, but also providing essential services like water and nutrient cycling, soil formation, equitable climate, and biological diversity (Dunlap and Catton, 2002; Smith et al., 2013). Land transformation has been the primary driving force of human alteration of terrestrial ecosystems, strongly interacting with most other aspects of global environmental change (Lambin et al., 2001; Steffen et al., 2015; Vitousek et al., 1997). Carbon emissions from land use and land-cover change contribute 12.5% to anthropogenic carbon emissions (Houghton et al., 2012), thus representing the second-largest source after fossil fuel combustion (van der Werf et al., 2009). In view of the serious danger that climate change poses to ecosystems and human welfare (Smith et al., 2009), the capacity of land to sequester carbon is one of its crucial functions. Besides the protection and restoration of forests, recent efforts to foster climate action like the "4 per 1000 initiative" under the framework of the Lima-Paris Action Agenda emphasise the importance of soil carbon which is also stored in agricultural ecosystems.

The livestock sector is a major driver of land related human interference with the Earth system, consuming 58 % of the economically used plant biomass (12.1 Pg/yr) in contrast to 12 % directly serving as food (Krausmann et al., 2008). Resulting overall land use of livestock production accounts for 80% of agricultural land (Steinfeld et al., 2006), where grazing land alone covers 25% of the Earth's land surface (FAOSTAT, 2016). Direct and indirect deforestation is the most critical aspect of land use change, with livestock playing a pivotal role through the establishment of new pastures or expansion of arable land to produce crops like soybeans in the wake of intensifying livestock feeding practices around the world (Herrero et al., 2009; Naylor et al., 2005; Nepstad et al., 2006). Conversion of forests to pastures represents 65-80% of deforestation in the Amazon (Herrero et al., 2009; Wassenaar et al., 2007). While cattle ranging is the major direct driver of forest clearing, soybean production indirectly triggers deforestation by boosting land prices and infrastructure development (Barona et al., 2010; Fearnside, 2005, 2001).

Accordingly, restraining land requirements is increasingly regarded as a key measure to alleviate detrimental impacts of livestock production on the environment (Smith et al., 2013; Steinfeld and Gerber, 2010; Wirsenius et al., 2010), either on the supply side by changes in livestock production systems or on the demand side by lower consumption of land-intensive livestock commodities. On the supply side, substantial differences in feed conversion efficiencies across regions and levels of intensification indicate a large potential to transform biomass flows within the global food system and attenuate pressures on natural resources (Bouwman et al., 2013; Havlík et al., 2014; Herrero et al., 2015, 2013; Weindl et al., 2015; Wirsenius et al., 2010). Intensification of livestock production systems does not only considerably alter feed and overall resource use per animal product, but it also affects the composition of feed baskets, shifting the focus from residues, food waste and grazed biomass to higher quality and nutrient-rich feed. However, resulting increase in the importance of cropland at the expense of pastures could impede carbon sequestration, since grasslands have a high root turnover and build up substantial soil organic carbon stocks (Conant et al., 2001; Don et al., 2011).

In consequence, understanding the link between livestock, land and carbon requires a detailed representation of feeding regimes and a comprehensive coverage of different land use types and related carbon pools. While several studies highlight the importance of feeding efficiencies and shifts in livestock production systems to attenuate pressures on land and to reduce greenhouse gas (GHG) emissions (Cohn et al., 2014; Havlík et al., 2014; Herrero et al., 2013; Valin et al., 2013), they consider aggregated carbon dioxide (CO_2) emissions without separating carbon pools and channels of land conversion or limit the scope to nitrous oxide (N_2O) and methane (CH_4) emissions. However, a dedicated coverage of soil carbon and non-forest land is essential for designing efficient climate protection schemes, since exclusion of non-forest carbon stocks from mitigation policies entails significant carbon leakage (Popp et al., 2014) and carbon stored in soils represents more than twice the amount found in the atmosphere (Smith, 2008).

This study aims at specifically addressing the impacts of future livestock production on the interplay between different managed and unmanaged land types and related trade-offs in terms of carbon losses from vegetation, litter and soils. Special attention is hereby given to sector-specific options to mitigate pressures on terrestrial ecosystems like changes in human diets and different livestock productivity pathways, either representing a catch-up of low productive systems to higher productivity levels, a stagnation of productivity in extensive systems or a moderate productivity reduction in intensive systems. For this aim, we apply a global economic land use model with geographically explicit representation of land quality and biophysical constraints, where links between livestock, land and crop production are established through regional and product-specific feed baskets that evolve with the productivity level, through manure provision, investments into research and development and trade flows.

2. Methods and data

2.1. Modelling framework

The Model of Agricultural Production and its Impact on the Environment (MAgPIE) is a global partial equilibrium land and water use model. It combines spatially explicit biophysical constraints with regional socioeconomic information for ten world regions (Table 1) to derive optimal resource allocation and agricultural production patterns (Bodirsky et al., 2014; Lotze-Campen et al., 2008; Popp et al., 2017, 2014; Stevanović et al., 2016). Possible future developments of the agricultural and land-use sectors are simulated in a recursive dynamic mode with a variable time step length of five or ten years on a timescale from 1995 to 2050 by minimizing a nonlinear global objective function defining global agricultural production costs.

Table 1. Socio-economic regions in MAgPIE.

Acronyms	MAgPIE regions
AFR	Sub-Sahara Africa
CPA	Centrally Planned Asia (incl. China)
EUR	Europe (incl. Turkey)
FSU	Former Soviet Union
LAM	Latin America
MEA	Middle East and North Africa
NAM	North America
PAO	Pacific OECD (Australia, Japan and New Zealand)
PAS	Pacific Asia
SAS	South Asia (incl. India)

Pasture productivity, crop yields under both rainfed and irrigated conditions, related irrigation water demand per crop, water availability for irrigation and carbon densities are simulated by the process-based, dynamic global vegetation and water balance model LPJmL (Lund-Potsdam-Jena model with managed Land) (Bondeau et al., 2007; Müller and Robertson, 2014) on 0.5 degree resolution and aggregated to 1000 clusters for this study (Dietrich et al., 2013). LPJmL simulates growth, production and phenology of 9 plant functional types (Sitch et al., 2003) and of 11 crop functional types as well as managed grassland (Bondeau et al., 2007). Water and carbon fluxes (gross primary production, auto- and heterotrophic respiration) are directly connected to vegetation patterns and dynamics through the linkage of transpiration, photosynthesis and plant water stress.

Food demand projections are exogenously calculated based on an econometric regression model for national caloric intake per capita, thus considering historical patterns and socio-economic assumptions on future income and population growth (Bodirsky et al., 2015, 2012; Valin et al., 2014), and provided for 16 food crop categories and 5 livestock commodities. Material demand is assumed to grow proportionally to food demand. Regional feed demand depends on livestock production quantities and regional system-specific feed baskets that evolve with livestock productivity trajectories. Global demand for agricultural commodities is allocated to the supply regions via trade dynamics based on an exogenous rate of trade liberalization, defining the proportion of agricultural goods that are, on top of historical trade patterns, traded according to comparative advantages (Schmitz et al., 2012). Through investments in research and development (R&D), the model can endogenously increase crop yields and pasture productivity, with the costs of technological change depending on the current technology level (Dietrich et al., 2014). More information on the model version underlying this study can be found in the SI appendix.

2.2. Land dynamics

Competition for land is explicitly addressed for the following land types: cropland, pasture, forest (including forestry), and other land (other natural vegetation such as savannahs and shrubland as well as abandoned agricultural land). Urban areas, covering around 1% of total land (Popp et al., 2017), are assumed to be static over time. Forest areas designated for wood production (about 30% of the initial global forest area) and pristine forests in protected areas (12.5% of global forests (FAO, 2010)) are excluded from conversion into agricultural land. The suitability of the land for crop cultivation further constrains the conversion of natural vegetation or pastures to cropland. The suitability of land is primarily determined using crop yields from LPJmL. Additionally, cropping can only occur on land that is at least marginally suitable for rainfed crop production with regard to climate, topography and soil type according to the Global Agro-Ecological Assessment (GAEZ) methodology on land suitability (Fischer et al., 2002; Krause et al., 2013; van Velthuizen et al., 2007). In response to production costs (see SI appendix A.1) and biophysical constraints, MAgPIE optimizes spatial distribution of crops and pasture within current agricultural land as well as the balance between land expansion, trade, and improvements in land productivity.

2.3. Carbon dynamics

Carbon emissions in MAgPIE are computed as the change in terrestrial carbon stocks from land conversion processes between simulated land types. Spatially explicit carbon stocks for all considered land types and carbon pools (vegetation, litter and soils) are calculated by multiplying pool- and land-specific carbon densities with land area. Negative carbon emissions occur when cropland is set-aside from agricultural production and subsequent ecological succession restores natural vegetation carbon stocks (Humpenöder et al., 2014), thus turning land into a sink for atmospheric carbon. In case of regrowth, vegetation carbon density increases over time along sigmoid growth curves which are based on a Chapman-Richards volume growth model (Murray and von Gadow, 1993; von Gadow and Hui, 2001) and parameterized using vegetation carbon density of natural vegetation. Carbon densities for vegetation, litter and soil carbon pools of natural vegetation (Fig. 1) are provided by LPJmL.

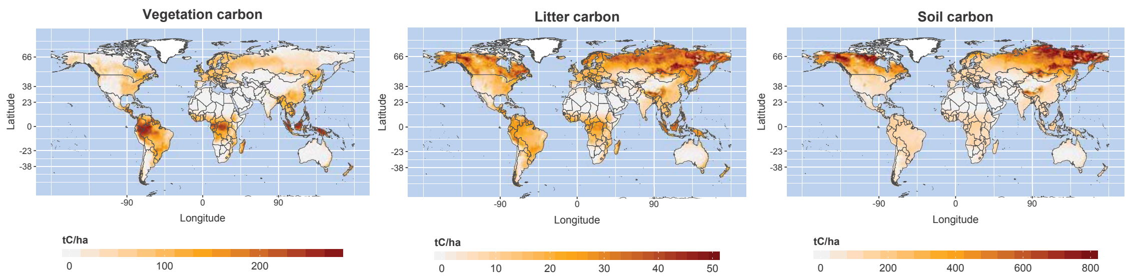

Fig. 1.Potential carbon densities for vegetation, litter and soil carbon pools in tC/ha calculated by LPJmL assuming that all terrestrial grid cells are covered with natural vegetation.

2.4. Livestock sector dynamics

Livestock products are supplied by five animal food systems (beef cattle, dairy cattle, pigs, broilers and laying hens). Feed conversion F_C (total feed per product in dry matter) and feed baskets F_B (demand for different feed types per product in dry matter) are derived by compiling system-specific feed energy balances (Weindl et al., submitted; Wirsenius, 2000; Wirsenius et al., 2010), using feed energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals as estimated by Wirsenius (2000). These estimates are based on standardized bio-energetic equations and include the minimum energy requirements for maintenance, growth, lactation, reproduction and other basic biological functions of the animals. Moreover, they comprise a general allowance for basic activity and temperature effects.

Non-linear regression models for feed conversion F_C and feed composition F_{comp} (share of different feed groups in feed baskets) with livestock productivity (annual production per animal [ton/animal/year]) as predictor permit the construction of productivity dependent feed baskets (SI appendix A.2). For F_C, best performance was observed by using a power function to describe the relationship between F_C and livestock productivity. In the case of F_{comp}, we use an additional proxy in our analysis, since the type of biomass used for feeding is only partially subject to universal aspects (e.g. the need for more energy-rich feed at higher productivity levels), whereas other aspects are influenced by geographical location, e.g. availability and costs of permanent pasture compared to cropland feed and agro-ecological as well as climatic conditions that favor selected feed items. Incorporation of spatial heterogeneity and climatic conditions into weighted non-linear regression models for F_{comp} is facilitated by a proxy based on Koeppen-Geiger climate zones (Portland State University, 2015).

2.5. Scenario description

Socio-economic drivers are parametrized in line with the „Middle of the Road" scenario of the Shared Socioeconomic Pathways (SSPs) for climate change research (Kriegler et al., 2017; O'Neill et al., 2014; Popp et al., 2017). In this scenario (SSP2), gross domestic product (GDP) and population trajectories reach global values of 230 trillion US Dollars (at 2005 prices and adjusted for purchasing power parity) and 9.1 billion people in 2050 (IIASA, 2013). Average per capita food demand in 2050 amounts to 3174 kcal per day, with a contribution of 21% animal-based calories (excluding fish; see SI appendix, Fig. S7). Global trade barriers are relaxed by 5% per decade.

Table 2. Overview of scenario setting.

Scenario		Description
Dietary choices	SSP2	Food demand trajectories according to the SSP2 narrative with an average per capita food demand of 3174 kcal per day and 21% animal-based products in dietary calories in 2050
	DEMI	Gradual change towards a demitarian Western diet with a share of animal-based products in dietary calories of no more than 15% in 2050
Livestock productivity	BASELINE	Livestock productivity trajectories according to the SSP2 narrative with medium pace in productivity increases and a slight catch-up of low productive systems
	DIVERGENCE	Continuation of historically observed very divergent productivity trends with little improvements in low productive systems
	CATCH-UP	SSP2 + further closure of the productivity gap by 45% for ruminant systems and by 60% for monogastric systems until 2050
	MODERATION	SSP2 + productivity reductions in highly productive systems to the level of 75% relative to the productivity frontier

We investigate six scenarios defined by assumptions on both *dietary choices* and *livestock productivity* trends. Supplementing the baseline diet scenario (SSP2), we define an alternative development of dietary patterns (SI appendix, Fig. S7), representing a gradual change of SSP2 diet projections to lower shares of animal-based calories in diets, with 15% as upper limit in 2050 for calories from livestock and fish (DEMI). With the share of animal-based calories being approximately half the currently observed level in OECD countries, the DEMI scenario builds upon the concept of a "demitarian" Western diet (Bodirsky et al., 2014; Stevanović et al., 2017; Sutton and Ayyappan, 2013).

The diet scenarios are combined with four alternative livestock productivity pathways (SI appendix, Fig. S8). Besides exploring impacts of productivity gains, which are often regarded as beneficial for resource efficiency, we also explore how de-intensification strategies could affect land and carbon dynamics. The BASELINE scenario, following the SSP2 narrative, is generally characterized by a medium pace in productivity improvements, but low-productive regions catch up to a certain extent (Popp et al., 2017). With little improvements in some regions' low productive systems, the DIVERGENCE scenario represents the continuation of historically observed very divergent productivity developments and is constructed by following the extrapolation of historical trends between 1970 and 2010, if they are lower than SSP2 projections. In contrast to the DIVERGENCE scenario, the ambitious CATCH-UP scenario assumes a further closure of the productivity gap, defined by top-performing countries in 2010, by 45% for ruminant systems and by 60% for monogastric systems until 2050. The MODERATION scenario explores a variation of SSP2 livestock productivity trends at the opposite end of the range, the highly intensive systems. Until 2050, these systems are assumed to experience a reduction in livestock productivity to the level of 75% relative to the productivity frontier defined by top-performing countries in 2010.

3. Results

3.1. Feed demand and agricultural biomass harvest

Future estimates of agricultural biomass harvest are considerably influenced by composition and level of feed demand (Fig. 2). Across the two diet and four livestock productivity scenarios, cropland production (both food and forage crops) increases by 44-97%, production of food crops rises by 46-64%, and grazed biomass changes by -31% to +69% between 2010 and 2050. In the SSP2 BASELINE scenario, global feed demand increases from 8280 Mt DM in 2010 to 11880 Mt DM in 2050 (+44%). In the same period, feed demand for food and forage crops almost doubles (4230 Mt DM in 2050).

Assuming a considerable CATCH-UP of low-productive systems, feed demand for food and forage crops reaches highest values (4390 Mt DM), while total feed demand defines the lower end of the range for SSP2 diets (11160 Mt DM). Stagnation of low productivity trends in some regions (DIVERGENCE) results in highest overall feed use in 2050 (14140 Mt DM, 71% increase), together with lowest levels of feed demand for food and forage crops (3770 Mt DM). In the MODERATION scenario targeting only highly productive systems, total feed demand is slightly higher than in the BASELINE, with feed demand for food crops being a little lower. Regarding the effects of dietary changes, we observe high potentials to reduce the amount of biomass needed to feed animals in 2050. While feed use almost doubles in the SSP2 BASELINE scenario in 2050 relative to 2010, it only increases by 3% for the DEMI BASELINE simulation and even decreases by 4% in the DEMI CATCH-UP scenario.

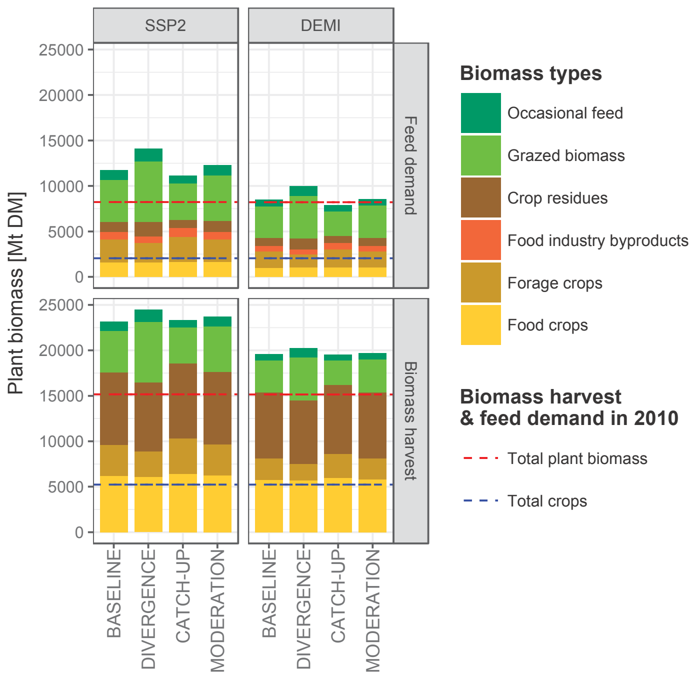

Fig. 2. Global feed demand and agricultural biomass harvest including food and forage crops, above-ground crop residues as well as grazed biomass in 2050 in Mt dry matter (DM). The red dashed line indicates total feed demand (upper panel) and agricultural biomass harvest (lower panel) in 2010. The blue dashed line specifies harvest of food and forage crops (without crop residues) in the lower panel and related feed demand in the upper panel in 2010. Note that feed demand for categories *food industry byproducts* and *food waste* of the upper panel is included in production of food crops in the lower panel.

3.2. Land use and land use change

The potential of the livestock sector to substantially alter land use dynamics is clearly visible on the global scale (Fig. 3). The interaction between cropland and pasture dynamics plays an important role for deforestation and is strongly influenced by livestock productivity trajectories, but also subject to demand-side preferences. In the SSP2 BASELINE scenario, total agricultural land increases from 4630 Mha in 2010 to 4830 Mha in 2050 as a result of substantial cropland expansion (+370 Mha, +26%) that is partly compensated by a reduction in pasture area (-170 Mha, -5%). By 2050, forest losses amount to 150 Mha, while conversion of other natural vegetation represents a minor contribution to land use change (50 Mha). Across all diet and productivity scenarios, projected deforestation ranges between 70 and 360 Mha. Dietary changes towards less livestock products reduce pressures on land, translating into lower cropland expansion (23-39% less than under SSP2 diets) and avoided deforestation (47-55%).

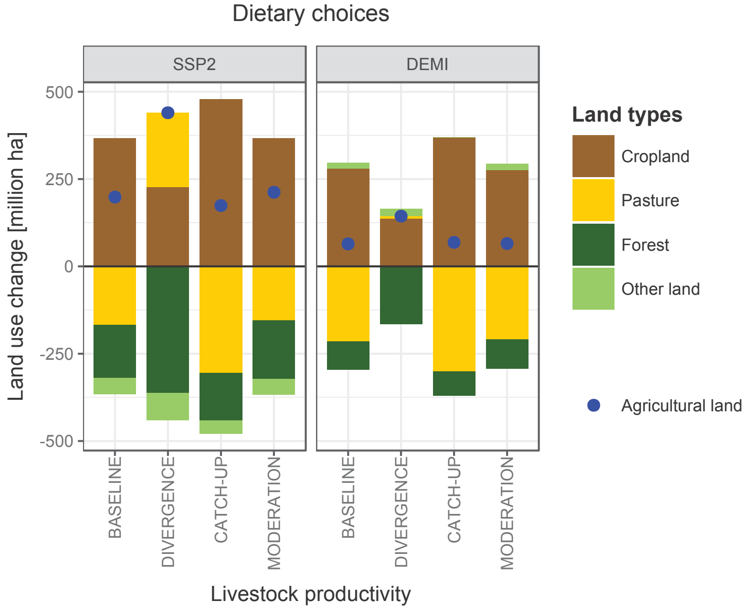

Fig. 3. Changes in global cropland, pasture, forest and other natural vegetation between 2010 and 2050 in Mha. Blue points indicate the net change in global agricultural land.

All scenarios involve expansion of cropland (10-35%) which increases with higher livestock productivity and decreases with lower consumption of livestock products. Implications for deforestation depend on the potential of pasture-to-cropland conversion to counterbalance increased land demand to grow crops. Reductions in pasture area in the wake of higher livestock productivity outpace related increases in cropland, thus entailing a land sparing effect. Only under stagnating low livestock productivity in some regions together with a growing demand for livestock products (SSP2 DIVERGENCE), we observe an increase in pasture area (+210 Mha) and consequently the highest estimate for deforestation. The MODERATION productivity scenarios entail very similar dynamics as the BASELINE scenarios, with slightly higher deforestation for SSP2 diets.

Global patterns of land use change are a congeries of diverse regional developments (Fig. 4). In Latin America, Sub-Saharan Africa and South Asia, land conversion processes across scenarios are strongly influenced by livestock productivity trends, resulting in a large regional spread of deforestation and loss of other natural ecosystems. In Centrally Planned Asia, Former Soviet Union, North America, Middle East and North Africa, land dynamics primarily react to dietary changes, ending forest conversion in North America and resulting in land abandonment and regrowth of natural vegetation in the Former Soviet Union. In the Middle East and North Africa, expansion of agricultural activities is heavily constrained by the scarcity of natural resources, with pasture being the only land resource available for cropland expansion. Establishment of new pastures, discernibly linked to loss of forests or other natural vegetation, is only simulated under the DIVERGENCE pathway with prevailing low productivities in the respective regions.

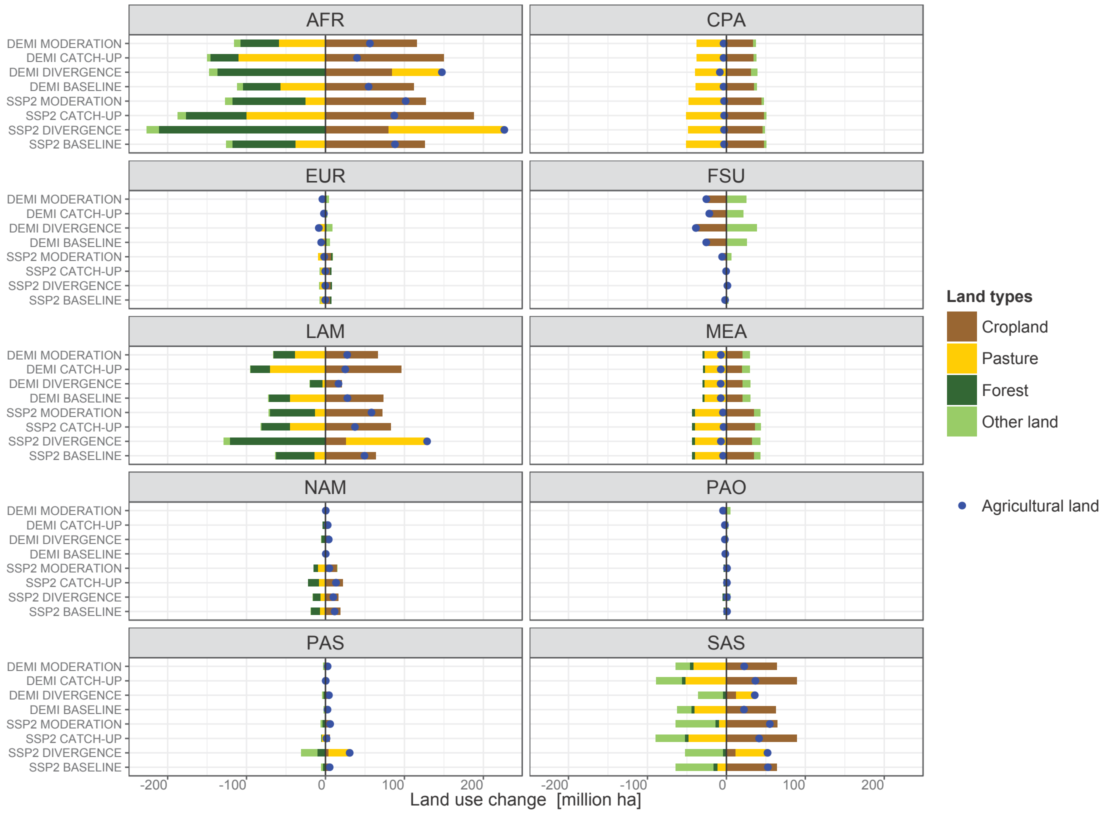

Fig. 4. Changes in regional cropland, pasture, forest and other natural vegetation between 2010 and 2050 in Mha. Blue points indicate changes in regional agricultural land defined as the sum of cropland and pasture.

Regional results highlight the important role of developments in Sub-Saharan Africa and Latin America for further alteration of terrestrial ecosystems. In Latin America, the SSP2 DIVERGENCE scenario entails considerable forest losses due to pasture expansion, while further cropland development is the main driver for forest clearing (16-57 Mha) across all other scenarios. Cropland expansion that goes along with higher livestock productivity and a growing market of high-quality feed can partly be realized by conversion of pastures. The response of land dynamics to productivity pathways also depends on the diet scenario. While for SSP2 diets, 121 Mha of the Amazonian Rainforest are lost under the DIVERGENCE pathway, deforestation in the respective DEMI scenario represents the lower bound of scenario estimates (16 Mha), due to a combination of indirect effects: alteration of trade flows and R&D investments into land productivity. Although higher exports of livestock products under DEMI scenarios (SI appendix, Fig. S18) counteract relaxing pressures due to dietary changes, deforestation rates are generally lower. In Sub-Saharan Africa, a strong relationship between higher livestock productivity and a shift from pasture to cropland activities is clearly visible across scenarios, accompanied by considerably lower deforestation. In contrast, if livestock productivity remains low, African forest ecosystems, e.g. the Central African rainforest, are projected to experience substantial clearance activities (see SI appendix, Fig. S11 for forest cover maps in 2050). Due to population growth and an increase of livestock products in diets even for the DEMI scenarios, livestock production is projected to increase tremendously.

3.3. Carbon dynamics

Agricultural expansion and losses of natural ecosystems across all scenarios drive further depletion of terrestrial carbon stocks, but by different orders of magnitude (Fig. 5). Until 2050, cumulative carbon releases amount to 20-80 Gt C, which is equivalent to 74-295 Gt CO_2 emitted to the atmosphere (Table 3). As in the case of deforestation, the predominant role of Sub-Saharan Africa and Latin America is clearly visible in our results, contributing 74-93% to global carbon losses. If low historical productivity improvements are assumed to continue in the future, both regions together are projected to double (DEMI) or triple (SSP2) their LUC carbon emissions compared to BASELINE trends. Thus, already intermediate livestock productivity improvements, as assumed under the BASELINE pathways for these regions, lead to substantial abatement of LUC emissions. The role of different land types within overall land dynamics affects the extent at which the different above and belowground carbon pools contribute to net carbon losses, both at the regional and global scale. In the SSP2 BASELINE scenario, changes in vegetation carbon account for 51%, depletion of soil carbon for 39% and losses of carbon in litter for 10% of total releases (124 Gt C).

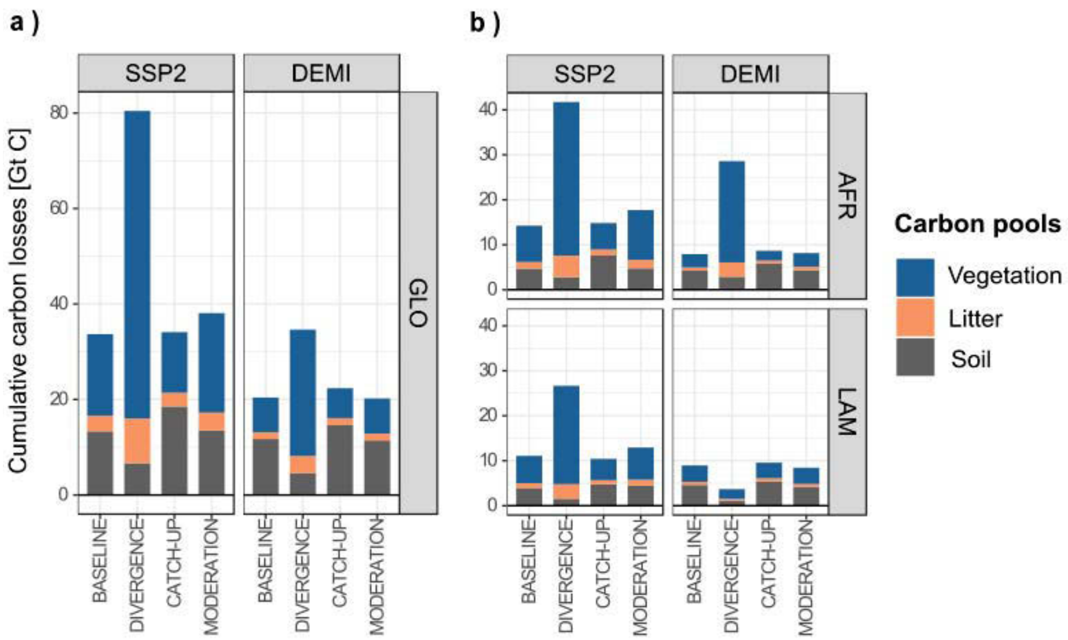

Fig. 5. Cumulative carbon losses between 2010 and 2050 in Gt C from vegetation, litter and soil carbon pools. The left panel (a) illustrates global values and the right panel (b) shows values for Sub-Saharan Africa (AFR) and Latin America (LAM).

Table 3. Cumulative CO_2 emissions between 2010 and 2050 for all scenarios in Gt CO_2.

Diets	Productivity	Vegetation	Litter	Soil	All pools
SSP2	BASELINE	63	12	49	124
	DIVERGENCE	236	34	24	295
	CATCH-UP	47	10	68	125
	MODERATION	76	14	49	140
DEMI	BASELINE	27	5	43	75
	DIVERGENCE	97	13	17	127
	CATCH-UP	23	5	54	82
	MODERATION	27	5	42	74

CATCH-UP pathways entail very similar cumulative carbon losses compared to BASELINE productivity trends, with a higher contribution of soil carbon and a lower share of vegetation carbon. Even though deforestation is slightly lower, considerable pasture-to-cropland conversion processes deplete carbon stored in soils and counteract minor potential carbon savings from avoided deforestation. High deforestation, as triggered by the DIVERGENCE pathway in combination with SSP2 diets, results in high carbon emissions. However, these substantial net carbon releases and especially soil carbon losses are lower than if only considering loss of forest carbon stocks, as expanding pastures can also sequester significant amounts of carbon in soils. While in the SSP2 MODERATION scenario, deforestation and resulting carbon emissions are higher than in the BASELINE, no difference can be observed for a reduced consumption of livestock products. In the DEMI scenarios, expansion of cropland is in general less linked to deforestation and relies stronger on conversion of pastures, resulting in a higher contribution of soil carbon to total carbon releases. Across all productivity pathways, dietary changes towards less livestock products can substantially reduce cumulative carbon losses (34-57%).

3.4. Uncertainties in projected land and carbon dynamics

How demand- and supply-side scenarios alter land and carbon dynamics also depends on the role of intermediate processes such as reallocation of production through international trade and efforts to invest into yield improvements and pasture management. To understand the role of trade and land productivity for land use change and related emissions, we conduct a sensitivity analysis applying three additional scenario settings: a) ***Restricted trade*** (relative to the default SSP2 setting) where we assume that interregional trade patterns, in terms of self-sufficiency ratios and relative shares of regional trade flows, are constant over time; b) ***Liberalized trade*** where global trade barriers are relaxed by 10% per decade (instead of 5% as in the SSP2 default setting), which is close to observed liberalization trends of the last decade; and c) ***Exogenous yield*** where all standard productivity and diet scenarios are calculated with exogenous trajectories of crop yields and pasture productivity, based on the endogenously calculated crop and pasture productivity trends from the SSP2 BASELINE simulation in the default model setting.

A *restricted trade* regime with self-sufficiency ratios and relative export flows fixed to 1995 levels constrains the possibility to balance heterogeneous demand trajectories and differences in land availability and productivity across regions through interregional reallocation of production. As a result, we observe more cropland expansion, deforestation and CO_2 emissions, although limited options to conciliate increasing food demand and available resources in some regions simultaneously lead to higher investments into yield increasing technological change (TC). Due to the low flexibility in the system, the potential of dietary changes to attenuate land use change and related emissions (23-37% reduction in emitted CO_2) is low compared to other sensitivity settings.

In a *liberalized trade* setting, trade patterns endogenously respond to asymmetric regional developments and can compensate regional inefficiencies and imbalances between food demand and availability of natural resources. Production is allocated according to comparative advantages between regions, which could also favour locations where land is abundant and lead to lower incentives to invest into yield increases. Thus, impacts of trade liberalization on land and carbon dynamics are mixed and depend on overall development pathways of agriculture. In the case of the SSP2 BASELINE and MODERATION scenarios, trade liberalization entails higher forest losses and CO_2 emissions, while production costs and R&D investments are lower. In the case of diverging livestock productivity trends, however, a reallocation of trade flows and production can exploit the large heterogeneity of regional livestock productivities and feed efficiencies, resulting in avoided deforestation and mitigation of CO_2 emissions.

The comparison of scenarios assuming *exogenous yield trajectories* with default simulations highlight the buffering effect of yield increasing innovation and management. Efforts to invest into land productivity depend on land scarcity and are driven by demand- and supply-side pressures on the agricultural system. Scenarios with exogenous yield trajectories exclude this dampening effect, thus leading to stronger signals of changes in productivity pathways and dietary choices. Assuming persistent efforts to increase land productivity independent from demand trajectories, the land sparing effect of a reduced consumption of livestock products is more pronounced, with a decline in deforestation by 64-72% and emissions abatement by 63-78%.

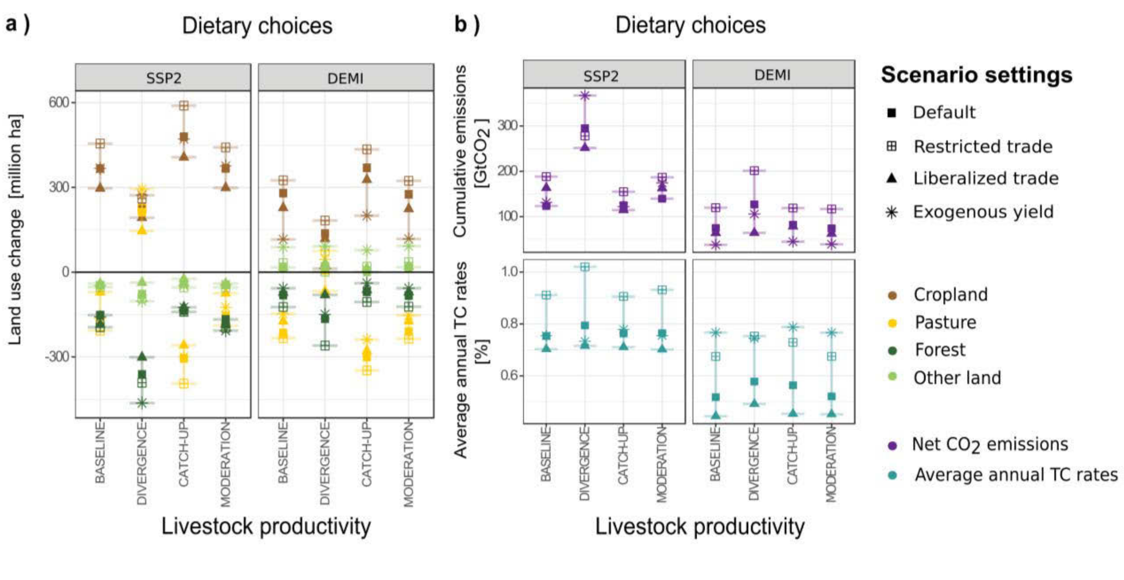

Fig. 6. Sensitivity analysis exploring the influence of international trade and yield trajectories on land use change and related emissions between 2010 and 2050. Panel a) illustrates changes in regional cropland, pasture, forest and other natural vegetation in Mha. Panel b) shows cumulative CO_2 emissions from changes in vegetation, litter and soil carbon stocks in Gt CO_2 and average annual TC rates.

Table 4. Impacts of dietary changes on deforestation and cumulative CO_2 emissions between 2010 and 2050 for all productivity scenarios in the default and additional model settings of the sensitivity analysis (changes in CO_2 emissions (%) for DEMI diet scenarios relative to SSP2 diet scenarios).

		BASELINE	DIVERGENCE	CATCH-UP	MODERATION
Deforestation	*Default*	-47%	-55%	-49%	-50%
	Restricted trade	-37%	-34%	-25%	-38%
	Liberalized trade	-61%	-73%	-50%	-62%
	Exogenous yield	-64%	-68%	-69%	-72%
CO_2 emissions	*Default*	-39%	-57%	-34%	-47%
	Restricted trade	-36%	-28%	-23%	-37%
	Liberalized trade	-61%	-74%	-31%	-62%
	Exogenous yield	-71%	-71%	-63%	-78%

4. Discussion

In the past decade, considerable efforts have been dedicated to better understand the environmental burden of livestock production and explore strategies for its abatement (Herrero et al., 2015). While earlier studies on the role of agricultural intensification in the sustainability context tend to focus on the crop sector (Burney et al., 2010; Tilman et al., 2002), recent work highlights that emission and land saving potentials of livestock system intensification by far outpace possible contributions from the crop sector (Cohn et al., 2014; Havlík et al., 2014, 2013; Valin et al., 2013). Moreover, there is evidence that shifts in dietary patterns have a similar potential to abate GHG emissions as an agricultural GHG tax policy, but without potentially negative effects on food prices (Stevanović et al., 2017). Building upon these insights, we further disentangle impacts of livestock productivity growth and dietary changes on land and carbon dynamics, focusing on the interplay between different land types and related trade-offs in terms of carbon losses from vegetation, litter and soils.

Development pathways of the livestock sector are studied within an integrated modelling framework that traces changes in feed demand through the whole agricultural and land use system. In our simulations, productivity gains involve an improvement of feed conversion efficiencies together with a shift from low-cost and low-energy feed, sourced from pastures or available as by-products from the agricultural supply chain, to cropland feed with higher nutrient densities, similar to findings obtained by Herrero et al. (2013). For ruminant systems, the resulting increase in the relative contribution of crops within feed rations outperforms the absolute reduction in feed per product. Our results indicate that increasing livestock productivity drives cropland expansion, whose consequences regarding deforestation depend on the relative reduction in pasture and the suitability of these areas for cropping. The rising importance of cropland for ruminant systems and the potential of pasture-to-cropland conversion to absorb pressures on forests and other natural vegetation challenge the perception that ruminant production does not directly compete with food crop production for resources and that required large land areas have little ecological opportunity costs (Bradford, 1999; Peralta et al., 2014).

Already minor productivity gains in extensive livestock production systems are an effective lever to avoid deforestation (50-58% reduction in BASELINE scenarios compared to DIVERGENCE pathways) and abate carbon emissions (41-58% reduction), since decreases in pasture area occur faster than expansion of cropland, thereby attenuating pressures on pristine ecosystems. Trade-offs with soil carbon losses equivalent of 25 Gt CO_2 are more than compensated by substantially lower emissions from vegetation carbon stored in native forests. However, if further proceeding to high productivity levels, trade-offs with ecosystem services on managed land are more pronounced since large-scale pasture-to-cropland conversion impair carbon sequestration in agricultural soils and biodiversity (Alkemade et al., 2013). Our simulations indicate that strong increases in livestock productivity involve a substantial depletion of soil carbon stocks, which can lead to a net increase of carbon emissions, although total feed demand and also deforestation are slightly lower under the ambitious CATCH-UP pathways compared to BASELINE scenarios.

Thus, a metric assessing the sustainability of livestock production that is solely oriented on feed or resource use efficiency may reach its limits in the case of significant conversion of pastures to cropland triggered by high livestock productivity gains. Solutions of this pasture-cropland dilemma related to livestock production include options to loosen the link between livestock productivity and cropland feed demand, e.g. by improving quality of non-cropland or by-product feed components. Promising suggestions include the development of dual purpose food/feed crops (Blümmel et al., 2009), adoption of improved deep-rooted pastures such as Brachiaria spp. (Thornton and Herrero, 2010) and silvio-pastoral systems, that combine pastures with trees and shrubs and simultaneously improve the productivity of primary as well as secondary production (Broom et al., 2013; Thornton and Herrero, 2010). These options represent viable intensification pathways for pastoral and mixed livestock-crop systems, involving low risks to aggravate land competition, but are only partially suited to attenuate the hunger for cropland in highly intensive systems.

While increasing productivity of extensive systems in developing regions is perceived as beneficial both with regard to environmental and social impacts like improved food security and livelihoods of poor farmers (Herrero et al., 2009; Steinfeld et al., 2006), there is an increasing concern about the downsides of industrial production technologies and large intensive operations associated with pollution of terrestrial as well as aquatic ecosystems through excessive nitrogen, pesticides and pathogens (Franzluebbers et al., 2014; Lemaire et al., 2014). Besides the introduction of organic and inorganic pollutants into agricultural, food and ecosystems, related issues such as decreasing soil fertility and soil organic matter, salt accumulation, loss of biodiversity, animal welfare, breeding of antibiotic-resistant pathogens and viruses, as well as the exploitation of non-renewable resources (e.g. groundwater and fossil fuels) question the long-term sustainability of modern livestock industries (Carvalho et al., 2010; Franzluebbers, 2007; Herrero et al., 2010; Russelle et al., 2007). Analysing land and carbon effects of moderate de-intensification of highly productive systems, we observe only small and ambiguous impacts on the system, starting with a slight growth in total feed demand and minor reduction in cropland feed, which translate into a small increase in deforestation and carbon emissions in the case of SSP2 diets and into almost identical land and carbon outcomes (compared to BASELINE) in the case of DEMI diet trajectories. Thus, potentially beneficial effects of moderate productivity decreases in intensive livestock systems on pollution and other aspects of the broader sustainability context are not jeopardized by impacts on land use and carbon losses, especially under reduced consumption of livestock products.

Positive effects of changing diets for climate protection are well documented (Aiking et al., 2006; Bajželj et al., 2014; Popp et al., 2010; Stehfest et al., 2009; Stevanović et al., 2017). While supply-side climate policies have repercussions on food prices and therefore on food availability in developing regions (Havlík et al., 2014; Stevanović et al., 2017), demand-side oriented strategies aim at a reduction in food consumption in affluent societies characterized by an overconsumption of livestock products. Besides synergies in the area of public health, a shift in consumption patterns has various co-benefits, like ecosystem recovery through abandonment of land and mitigation of nitrogen pollution (Bodirsky et al., 2014; Springmann et al., 2016; Stehfest et al., 2009). Our estimates of the annual carbon mitigation potential until 2050 are in the range of 1.1-4.2 Gt CO_2/yr for our default model setting, which is lower than 5.6 Gt CO_2eq/yr and 5.9 Gt CO_2eq/yr suggested by Stevanović et al. (2017) and Bajželj et al. (2014). While both studies use trajectories of dietary changes comparable to our DEMI diet scenario, they additionally assume a 50% food waste reduction and also account for non-CO_2 emissions which are projected to represent the major contribution of agricultural emissions over the 21st century. The spread of our estimates, which amounts to 0.9-6.5 Gt CO_2/yr if including results of the sensitivity analysis, indicates a strong dependence of climate benefits of changing consumer preferences on future productivity pathways in the livestock and crop sector, as well as on trade regulations.

Our results show that theoretical potentials of flexible trade flows to exploit regional differences in feed conversion efficiency through interregional reallocation of production only unfold in scenarios that assume prevailing large disparities of regional livestock production systems. Comparative advantages of some regions characterised by high resource availability can dampen efforts to invest into land productivity, with detrimental consequences for deforestation and carbon emissions, similar to dynamics attested by Schmitz et al. (2012). However, Havlík et al. (2014) suggest that intra- and interregional relocation of livestock production could contribute 49% of total emission abatement if incentivized by a global carbon price. In case that relative trade flows are fixed to 1995 levels, the inflexibility of the system generally leads to higher carbon emissions and constrains the potential of dietary changes to attenuate CO_2 emissions in our scenarios.

In our study, highest carbon savings from changing diets (63-78%) can be achieved if relaxed pressures on land have no negative repercussions on pasture management and productivity growth in the crop sector, emphasizing the importance to combine efforts in the crop and livestock sector to enable synergies for climate protection, in line with findings obtained by Valin et al. (2013). Moreover, our two-dimensional scenario matrix reveals that the spread of cumulative carbon emissions (between 2010 and 2050) associated with the explored productivity pathways is high for SSP2 diets (125-295 Gt CO_2), while dietary changes towards less livestock products smooth differences (74-127 Gt CO_2). Thus, a reorientation of consumer preferences would allow for a larger option space to develop regional livestock systems, progressing from a “land and carbon-only” approach to a broader sustainability metric that also considers animal well-being, livelihoods, water resources, biodiversity and pollution through various organic and inorganic substances.

5. Conclusion

If the growing demand for livestock products in developing countries is to be met without improvements in historically observed low livestock productivities in some regions, substantial increases in feed demand would imply massive forest and carbon losses. However, already intermediate livestock productivity gains can halt the expansion of pastures into pristine ecosystems and substantially reduce net land requirements for agricultural production, with significant benefits for climate change mitigation. In contrast, ambitious productivity increases that still slightly improve feed and land use efficiency involve trade-offs with carbon sequestration in agricultural soils, thereby possibly increasing net carbon emissions. At the same time, moderate de-intensification of highly intensive systems has negligible

impacts on land and carbon losses, thus not jeopardizing potentially beneficial effects on pollution, animal welfare and other aspects of the broader sustainability context.
On the demand side, reducing the consumption of livestock products to 15% animal-based calories in diets until 2050 can significantly abate LUC emissions by up to 78%. However, the carbon saving potential of changing diets depends not only on livestock productivity pathways, but also on productivity trends in the crop sector, pasture management and on other boundary conditions of agricultural production such as trade regimes. Thus, preference-based strategies aiming at behavioural change have to go hand in hand with supply-side oriented schemes to increase the resource efficiency of livestock production as well as with dedicated forest and climate protection policies, which counteract resource inefficiencies in global trade patterns, prevent interregional leakage and incentivize efforts to invest in the sustainable intensification of the whole agricultural and food system.

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Livestock and human use of land: productivity trends and dietary choices as drivers of future land and carbon dynamics

Supplementary information (SI Appendix)

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Appendix A. Extended methodology

A.1. Modelling framework

MAgPIE is a partial equilibrium, non-linear mathematical programming, agro-economic model which integrates geographically explicit information on land quality and biophysical constraints as well as regional socioeconomic information for ten world regions (Fig. S1) into an economic decision making process (Bodirsky et al., 2014; Lotze-Campen et al., 2008; Popp et al., 2014; Stevanović et al., 2016). Possible future developments are simulated in a recursive dynamic mode by minimizing a nonlinear global objective function for a variable time step length of five or ten years. The simulation period starts in the calibration year 1995, which allows for a consistency check and benchmarking between projections and statistical data since 1995. Due to computational constraints, geographically explicit information on 0.5 degree resolution was aggregated to 1000 cluster for this study (Dietrich et al., 2013). The core model code is written in the GAMS (Generalized Algebraic Modelling System) programing language using the CONOPT non-linear programming solver. Simulations are generated with model-revision 10007.

Food demand projections, which are calculated based on an econometric regression model for national caloric intake per capita and depend on income and population scenarios (Bodirsky et al., 2012, 2015; Valin et al., 2014), are exogenous to the model and provided for 16 food crop categories and 5 livestock commodities. Material demand grows proportionally with food demand. Regional feed demand is endogenously calculated depending on livestock production quantities and regional system-specific feed baskets that evolve with livestock productivity trajectories. During the processing of crops into refined food commodities, food industry byproducts are generated which are very valuable as feed due to their high nutrient contents and intensely traded. The generation of food industry byproducts is linked to the domestic supply of associated crops based on fixed regional processing rates. If future feed demand for crop residues or food industry byproducts surpasses production, alternative feed like food or forage crops of at least the same nutritional value is provided (e.g. soybeans), thus driving agricultural biomass production and land use. Global demand for agricultural commodities is allocated to the supply regions via trade dynamics based on an exogenous rate of trade liberalization, defining the proportion of agricultural goods that are, on top of historical trade patterns, endogenously traded according to comparative advantages (Schmitz et al., 2012). Assuming medium rates of trade liberalization, global trade barriers are relaxed by 5% per decade, which is less than observed liberalization trends.

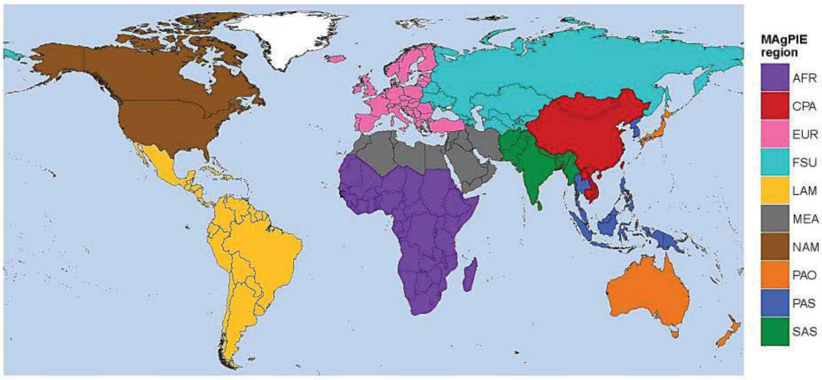

Fig. S1. MAgPIE world regions (AFR: Sub-Saharan Africa; CPA: Centrally-planned Asia incl. China; EUR: Europe incl. Turkey; FSU: Former Soviet Union; LAM: Latin America; MEA: Middle East/North Africa; NAM: North America; PAO: Pacific OECD, i.e. Japan, Australia, New Zealand; PAS: Pacific Asia; SAS: South Asia incl. India).

Input of local biophysical information (pasture productivity, crop yields under both rainfed and irrigated conditions, related irrigation water demand per crop, water availability for irrigation, carbon densities) is provided by the global crop model LPJmL (Lund-Potsdam-Jena with managed Land) (Bondeau et al., 2007; Müller and Robertson, 2014) on the gridded resolution 0.5°×0.5° geographic longitude-latitude. LPJmL is a process-based model which simulates natural vegetation at the biome level by nine plant functional types (Sitch et al., 2003) and agricultural production by 12 crop functional types as well as managed grass (Bondeau et al., 2007; Lapola et al., 2009). Simulation of water fluxes (interception, evaporation, transpiration, soil moisture, snowmelt, runoff, discharge) as well as carbon fluxes (gross primary production, auto- and heterotrophic respiration) and pools (in leaves, sapwood, heartwood, storage organs, roots, litter and soil) explicitly accounts for the interplay between natural and agricultural vegetation. Carbon and water fluxes are directly related to vegetation patterns and dynamics through the linkage of transpiration, photosynthesis and plant water stress. The photosynthetic processes are modelled according to Farquhar et al. (1980) and Collatz et al. (1992). At sowing, photosynthesis in LPJmL starts on the basis of leaf area index supplied from seed reserves. The daily assimilation by photosynthesis is allocated to four carbon pools: leaves, roots, harvestable storage organs (e.g. grains for cereals), and a pool representing stems and mobile reserves. At harvest, the biomass fraction of the storage organs is considered the harvested yield.

To inform the decision making process in MAgPIE, biophysical suitability of land and conditions for agricultural production have to be provided beyond the extent of land that is currently under agricultural management. Therefore, crop yield simulations from LPJmL assume that all crops are grown in all grid cells to assess possible crop productivity also in areas currently not used for crop cultivation. In seven individual LPJmL runs, crop yields are derived for seven different management intensity levels. Cropping intensities are selected to match observed yields from the FAO at country level. An additional LPJmL simulation assumes that all terrestrial grid cells are covered with natural vegetation, which involves a spin-up period of 1000 years to bring vegetation patterns and carbon pools into equilibrium. Results from the simulation of natural vegetation are used to provide data on carbon densities and water availability for MAgPIE.

Land use patterns in the initial year 1995 of the simulation period (Fig. S2) are defined by a spatially-explicit dataset of the following land pools: cropland, pasture, forest (including forestry), other land (other natural vegetation such as savannahs and shrubland; abandoned agricultural land), and urban areas which are static over time (Krause et al., 2013; Popp et al., 2014). Accounting for forest area designated for wood production (about 30% of the initial global forest area) and forests in protected areas which represent about 12.5% of global forests (FAO, 2010), parts of semi-natural and undisturbed natural forests are excluded from conversion into agricultural land. Not all land is suitable for cropping due to terrain- and agro-edaphic constraints. Therefore, natural vegetation or pastures can only be converted into cropland if the land is at least marginally suitable for rainfed crop production with regard to climate, topography and soil type according to the Global Agro-Ecological Assessment (GAEZ) methodology on land suitability (Fischer et al., 2002; Krause et al., 2013; van Velthuizen et al., 2007).

Following cost types are integrated into the optimization: Production costs per area are derived from the Global Trade Analysis Project (GTAP) Database (Narayanan and Walmsley, 2008) and contain factor costs for labour, capital and intermediate inputs (Dietrich et al., 2014). Through investments in research and development (R&D), the model can endogenously increase crop yields and pasture productivity, with the costs of technological change depending on the current technology level (Dietrich et al., 2014). Expansion of managed land is associated with land conversion costs, which are estimated on the basis of marginal access costs from the Global Timber Model (Sohngen et al., 2009) and account for basic infrastructure investments and preparation of converted land (Krause et al., 2013; Popp et al., 2011). Irrigation costs include investment costs for establishing new irrigation infrastructure, which are based on Worldbank data (Jones, 1995) and annual costs for operating irrigation systems (Bonsch et al., 2014). Following an approach by Calzadilla et al. (2011), the rent associated with irrigation water application is calculated from the GTAP land rent (Narayanan and Walmsley, 2008) and used as a proxy for the operation and maintenance costs of irrigation infrastructure. Lastly, the global objective function involves intraregional transport costs, thus integrating information about market access into the decision process where to allocate agricultural activities. Expenditures for transportation depend on the distance of the production site to markets, the quality of the infrastructure (both based on a detailed data set on travel time (Nelson, 2008)) as well as average transport costs for different commodities based on GTAP.

Agricultural land use in MAgPIE is induced by 17 cropping activities (16 related to food crops and one to forage crops) allocated to cropland and by livestock grazing on permanent pasture, required to satisfy demand for food, feed, seed and materials. In view of involved production costs and biophysical constraints, MAgPIE simulates major dynamics of the agricultural sector like R&D investments (Dietrich et al., 2012, 2014) and associated increases in both crop yields and biomass removal through grazing on pastures, land use change (including deforestation, abandonment of agricultural land and conversion between cropland and pastures), interregional trade flows, and irrigation.

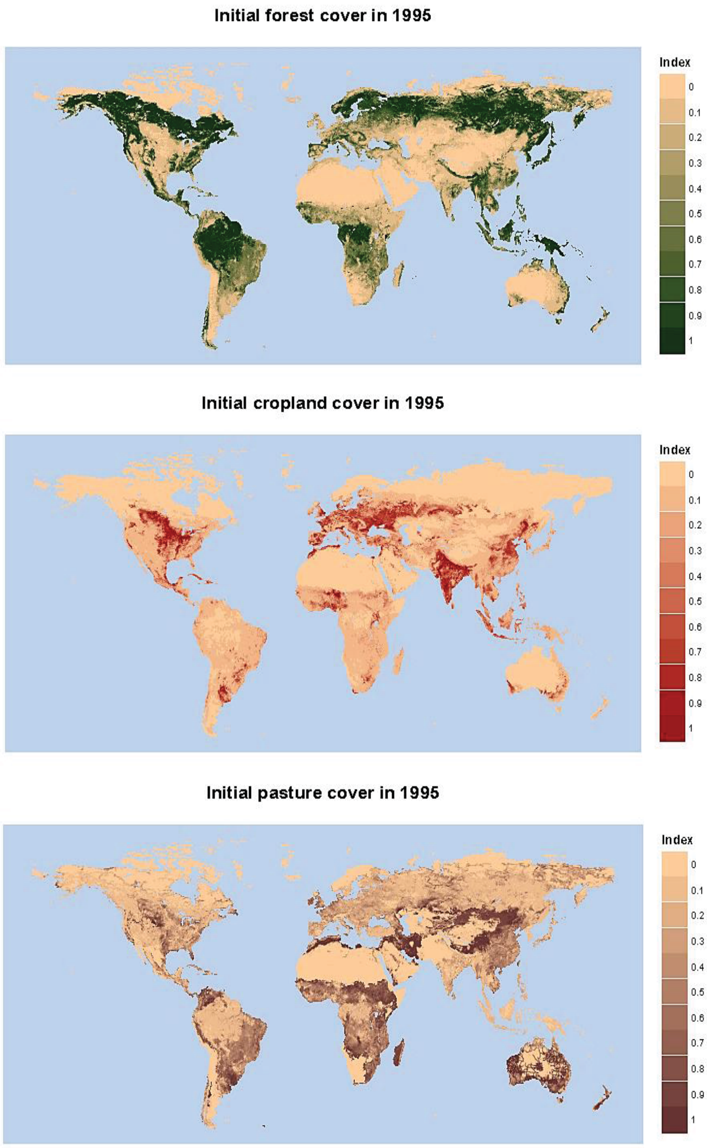

Fig. S2. Initial spatially explicit land use patterns in 1995 for forest, cropland and pasture, used as input in the MAgPIE model. Colours indicate the share of the respective land type in each cell.

Carbon emissions are computed as the change in terrestrial carbon stocks due to land conversion processes of simulated land types in MAgPIE. Spatially explicit carbon stocks for all considered land types and carbon pools (vegetation, litter and soils) are calculated by multiplying pool- and land-specific carbon densities with land area. Vegetation, litter and soil carbon densities of forests and other pristine non-forest vegetation (e.g. savannahs) are derived from a dedicated LPJmL simulation assuming that all terrestrial grid cells are covered with natural vegetation and involving a spin-up period of 1000 years to bring vegetation patterns and carbon pools into equilibrium. Cropland and pasture carbon densities are estimated based on LPJmL and data from IPCC (2006) (chap 5–6, table 5.5 and 6.2). Negative carbon emissions occur when cropland is set-aside from agricultural production. Subsequent ecological succession results in the restoration of natural vegetation carbon stocks (Humpenöder et al., 2014). In case of regrowth, vegetation carbon density increases over time along sigmoid growth curves which are based on a Chapman-Richards volume growth model (Murray and von Gadow, 1993; von Gadow and Hui, 2001) which is parameterized using vegetation carbon density of natural vegetation from LPJmL and climate region specific Mean Annual Increment (MAI) and MAI culmination age (IPCC, 2006). Litter and soil carbon densities of abandoned agricultural land are assumed to increase linearly towards the values of natural vegetation within a time horizon of 20 years (IPCC, 2000).

A.2. Non-linear regression models for feed conversion and feed composition

Livestock products are supplied by five animal food systems (beef cattle, dairy cattle, pigs, broilers and laying hens). Country-level feed conversion F_C (total feed per product in dry matter) and feed baskets F_B (demand for different feed types per product in dry matter) are derived by compiling system-specific feed energy balances (Weindl et al., submitted; Wirsenius, 2000; Wirsenius et al., 2010), using feed energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals as estimated by Wirsenius (2000).

a)

b)

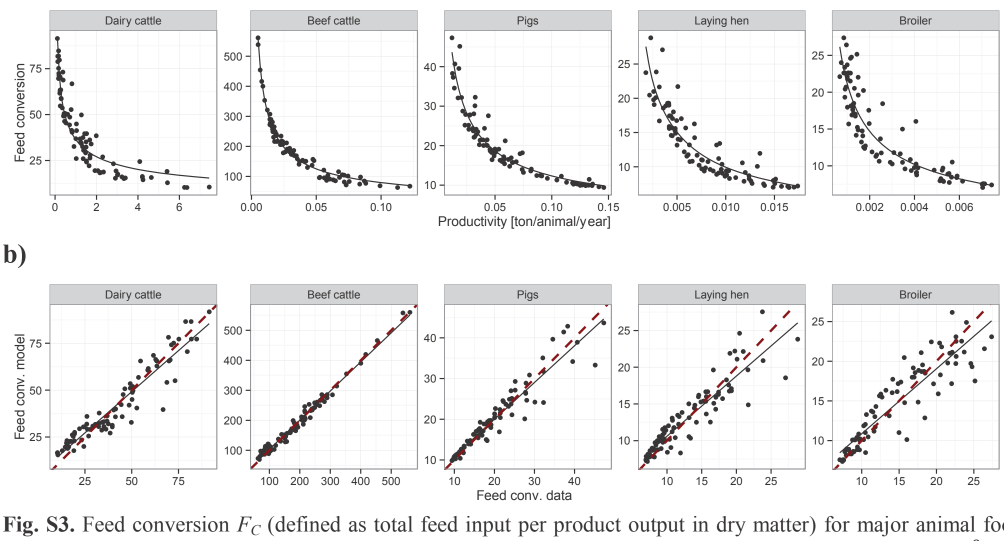

Fig. S3. Feed conversion F_C (defined as total feed input per product output in dry matter) for major animal food systems plotted against livestock productivity P in 1995 and model estimation with formula $y \sim \alpha x^{\beta}$ (a). Comparison of data and model estimates with linear regression (solid line) and 1:1 line (dashed line) (b).

To facilitate projections of feed conversion F_C and feed baskets F_B, we create regression models with livestock productivity P (annual production per animal [ton fresh matter/animal/year]) as predictor (Weindl et al., submitted). For beef cattle, pigs and broilers, P is defined as meat production per animals in stock (e.g. total cattle herd) and for dairy cattle and laying hen as milk or egg production per producing animals (e.g. milk cows). Data processing and statistical analyses are conducted applying the programming language and statistical software R (R Core Team, 2015).

For feed conversion F_C, best performance can be observed using a power function to describe the relationship between F_C and livestock productivity P as predictor variable: $F_C(P) = \alpha P^{\beta}$. We included only countries into our analysis that represent at least 0.001% of global production related to each of the five livestock commodities under consideration. Fig. S3a) displays the model estimation for F_C and Fig. S3b) illustrates the overall fit of the models, which are statistically highly significant with a coefficient of determination of 0.98, 0.90, 0.91, 0.82 and 0.83 for beef cattle, dairy cattle, pig, broiler and laying hen systems.

Table S1. Regression parameters for feed conversion F_C with formula $y \sim \alpha x^{\beta}$. Significance levels for p-values are denoted by (***): p < 0.001, (**): p ∈ [0.001, 0.01), (*): p ∈ [0.01, 0.05), (.): p ∈ [0.05, 0.1).

Animal food system	Parameter	Value	SE	p-value
Beef cattle	α	17.5262	0.6874	< 0.001 (***)
	β	-0.6556	0.0092	< 0.001 (***)
Dairy cattle	α	36.3321	0.8421	< 0.001 (***)
	β	-0.4256	0.0170	< 0.001 (***)
Pigs	α	3.1242	0.2226	< 0.001 (***)
	β	-0.5963	0.0201	< 0.001 (***)
Broiler	α	0.5584	0.1088	< 0.001 (***)
	β	-0.5262	0.0297	< 0.001 (***)
Laying hen	α	0.6445	0.1016	< 0.001 (***)
	β	-0.5942	0.0292	< 0.001 (***)

Regarding feed composition F_{comp}, we tested different groupings of feed types to reveal a relationship between the share of these groups within feed baskets F_B and P. For cattle food systems, we observe best performance for F_{comp} defined as the share of crop residues, occasional feed and grazed biomass within the feed rations. For pigs, best performance was apparent for defining F_{comp} as the complement of primary food items in pig feed baskets, i.e. the share of food waste, dedicated forage crops, occasional feed like scavenging, food industry byproducts and crop residues within feed rations. In the case of feed composition F_{comp}, incorporation of spatial heterogeneity and climatic conditions into the analysis is facilitated by considering Koeppen-Geiger climate zones. For each country, we calculate the share of population living in four aggregated groupings of climate zones (Table S2), using a comprehensive data set downloaded from Portland State University (2015).

Table S2. Grouping of climate zones.

Group	Koeppen-Geiger climate zones
CTrop	Tropical rainforest climate (Af), Monsoon variety of tropical rainforest climate (Am), Tropical savannah climate (Aw)
CArid	Steppe climate (BS), Desert climate (BW)
CTemp	Mild humid climate with no dry season (Cf), Mild humid climate with a dry summer (Cs), Mild humid climate with a dry winter (Cw)
CCold	Snowy-forest climate with dry winter (DW), Snowy-forest climate with a moist winter (Df), Polar ice climate (E), Highland climate (H)

We calculate the share of population living in one aggregated climate group ζ based on the groupings *CTrop, CArid, CTemp* and *CCold*, that can be used as a proxy to explain spatial heterogeneity of feed composition. Best performance is achieved by defining $\zeta \coloneqq CArid + CCold$ as aggregated climate group for cattle systems and by $\zeta \coloneqq CCold$ for pigs. For weighted non-linear regression models, we apply the following functional relationship F_{KG} for feed composition F_{comp}, defined as the linear combination of two asymptotic functions of P with the climate-zone specific factor ζ:

$$F_{KG}(P) = \zeta * \left(1 - \frac{\alpha P^3}{(0.1 + \alpha P^3)}\right) + (1 - \zeta) * \left(1 - \frac{\beta P^3}{(0.1 + \beta P^3)}\right).$$

a) **b)**

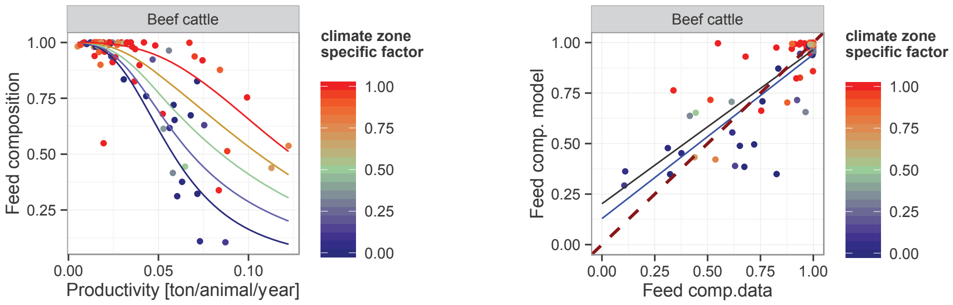

Fig. S4. Feed composition F_{comp} (defined as share of crop residues, occasional feed and grazed biomass in feed baskets) for beef cattle systems plotted against livestock productivity P in 1995 and model estimation F_{KG} (a). Comparison of data and model estimates with weighted linear regression (solid blue line with green shaded area) and unweighted linear regression (solid black line with gray shaded area) as well as 1:1 line (dashed line) (b).

Country-level shares of crop residues, occasional feed and grazed biomass within feed baskets of beef and dairy cattle are presented together with the respective model estimation by Fig. S4 and Fig. S5. Weighted linear regressions between model estimates and data are statistically highly significant with a coefficient of determination of 0.84 and 0.71 for the beef cattle and dairy cattle system.

a) **b)**

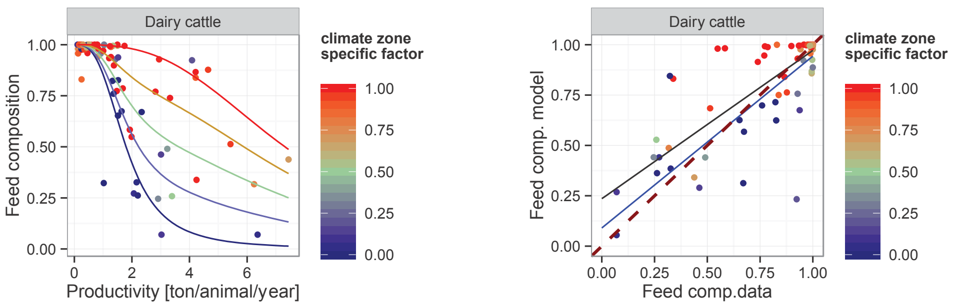

Fig. S5. Feed composition F_{comp} (defined as share of crop residues, occasional feed and grazed biomass in feed baskets) for dairy cattle systems plotted against livestock productivity P in 1995 and model estimation F_{KG} (a). Comparison of data and model estimates with weighted linear regression (solid blue line with green shaded area) and unweighted linear regression (solid black line with gray shaded area) as well as 1:1 line (dashed line) (b).

Fig. S6a) shows country-level shares of food waste, dedicated forage crops, occasional feed, food industry byproducts and crop residues within the feed baskets of pigs as well as the model estimation which depends on the climate-zone specific factor ζ. The overall fit of the model, as illustrated by Fig. S6b), is statistically highly significant with a coefficient of determination of 0.67.

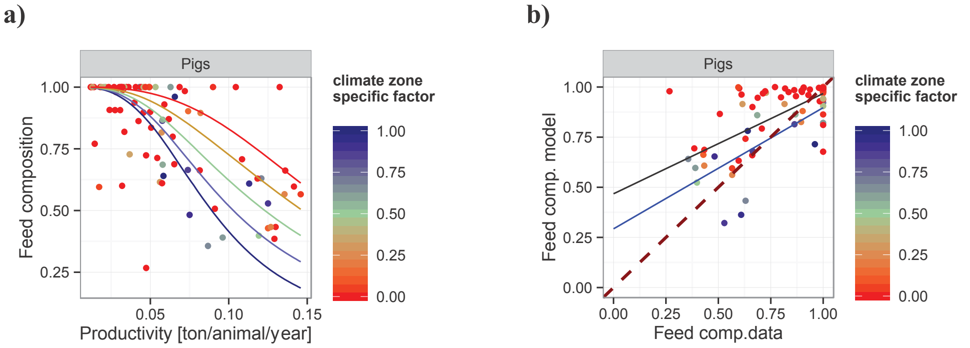

Fig. S6. Feed composition F_{comp} (defined as share of food waste, dedicated forage crops, occasional feed, food industry byproducts and crop residues) for pig systems plotted against livestock productivity P in 1995 and model estimation F_{KG} (a). Comparison of data and model estimates with weighted linear regression (solid blue line with green shaded area) and unweighted linear regression (solid black line with gray shaded area) as well as 1:1 line (dashed line) (b).

Table S3. Regression parameters for feed composition F_{comp} using a linear combination of two asymptotic functions of P with the climate-zone specific factor ζ. Significance levels for *p*-values are denoted by (***): p < 0.001, (**): p ∈ [0.001, 0.01), (*): p ∈ [0.01, 0.05), (.): p ∈ [0.05, 0.1).

Animal food system	Parameter	Value	SE	*p*-value
Beef cattle	α	1.5519	0.1521	< 0.001 (***)
	β	1.9993	0.3425	< 0.001 (***)
Dairy cattle	α	0.3987	0.0036	< 0.001 (***)
	β	0.6367	0.0143	< 0.001 (***)
Pigs	α	1.7334	0.3102	< 0.001 (***)
	β	1.3988	0.1103	< 0.001 (***)

A.3. Supplementary information on scenario assumptions

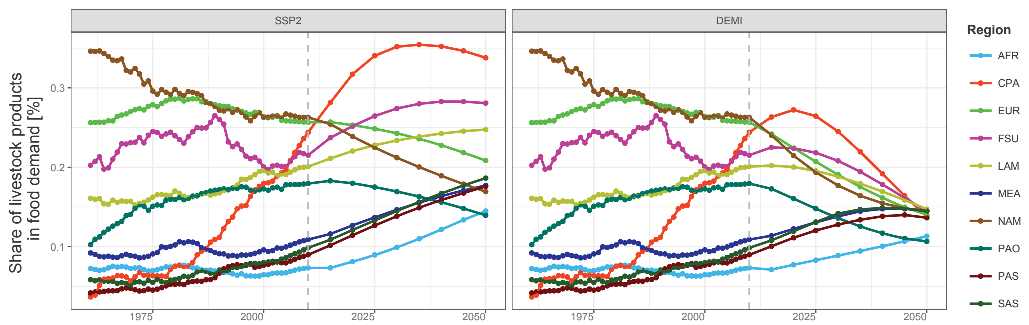

Fig. S7. Share of livestock products (excluding fish) in total calorie intake per person per day for all world regions. Historical development (left of the vertical dashed line) according to FAOSTAT (2013) and future developments (right of the vertical dashed line) for the two diet scenarios.

We explore six scenarios defined by assumptions on both dietary patterns and livestock productivity. In addition to the baseline diet scenario (SSP2), we consider an alternative development of dietary preferences (Fig. S7), which represents a gradual change of SSP2 diet projections to lower shares of animal-based calories in diets, with 15% as upper limit in 2050 for calories from livestock and fish (DEMI). Fig. S7 shows the temporal development of the contribution of livestock products to total calorie intake per person per day for all world regions and the two diet scenarios, including the historically observed development (FAOSTAT, 2013). Fig. S8 illustrates the temporal development of regional livestock productivity *P* for all products and the four productivity scenarios. The DIVERGENCE scenario represents the continuation of historically observed divergent trends. The ambitious CATCH-UP scenario assumes a further closure of the productivity gap, defined by top-performing countries in 2010, by 45% for ruminant systems and by 60% for monogastric systems until 2050. In the MODERATION scenario, highly intensive systems are assumed to experience a reduction in livestock productivity until 2050 to the level of 75% relative to the productivity frontier defined by top-performing countries in 2010.

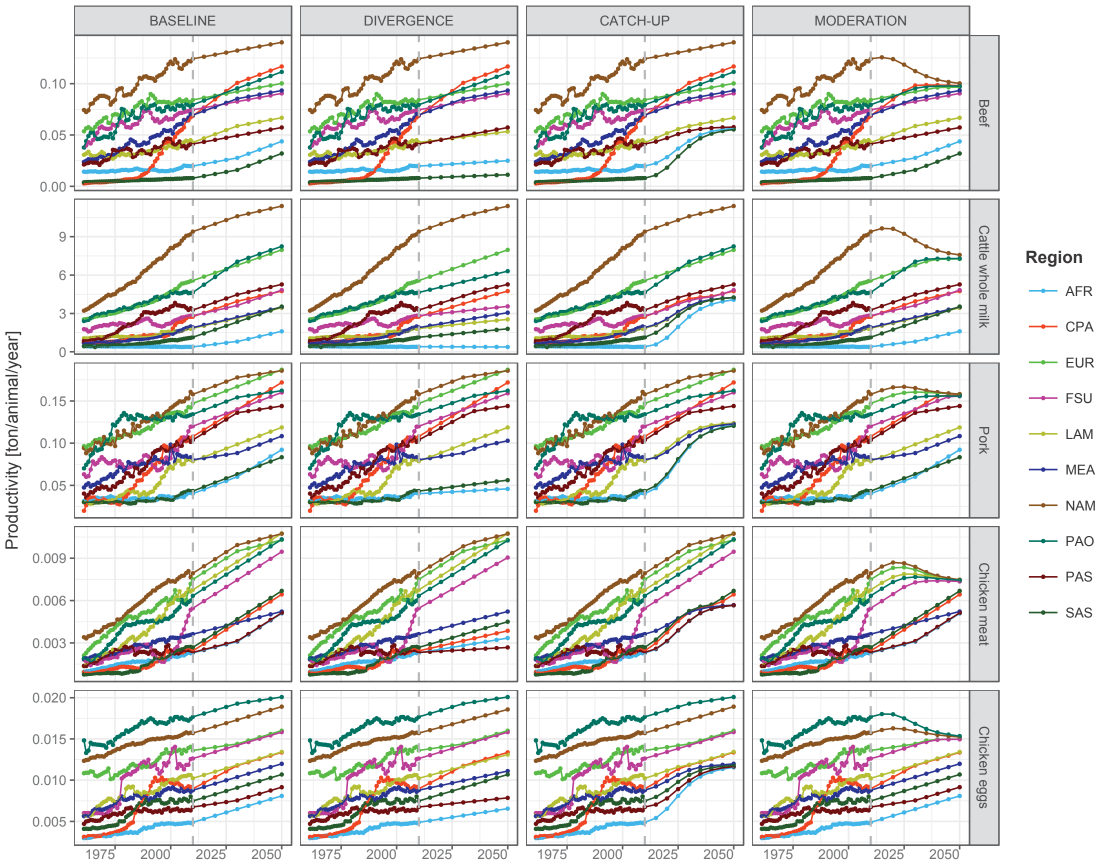

Fig. S8. Livestock productivity *P* (annual production per animal [ton/animal/year]) for all world regions and livestock products. Livestock productivity for beef cattle, pigs and broilers is defined as meat production per animals in stock (i.e. total cattle herd) and for dairy cattle and laying hens as milk or egg production per producing animals (i.e. milk cows). Historical development (left of the vertical dashed line) according to FAOSTAT (2013) and future developments (right of the vertical dashed line) for the four productivity scenarios.

Appendix B. Supplementary results

B.1. Regional feed baskets for all animal food systems in 2000

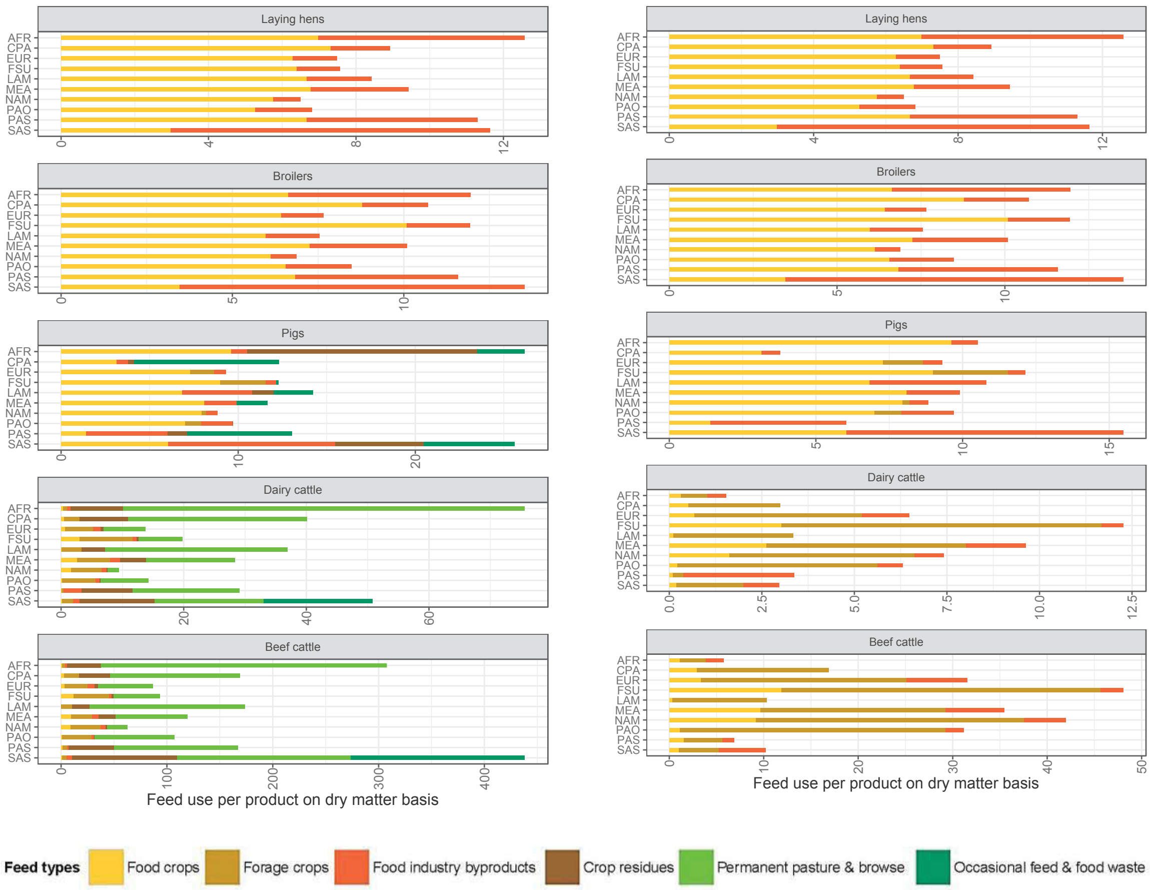

Fig. S9. Regional feed baskets (left panel) in 2000 for all animal food systems expressed as units of feed used to generate one unit product on dry matter basis. The right panel shows the fraction of feed baskets that is related to cropland harvest, i.e. required crop input per generated livestock product. Note that feed use includes energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals. For the dairy cattle system, product output comprises whole-milk as well as meat from milk cows (see Wirsenius (2000) for more information on herd structures).

B.2. Regional feed baskets for all animal food systems in 2050 for the BASELINE scenario

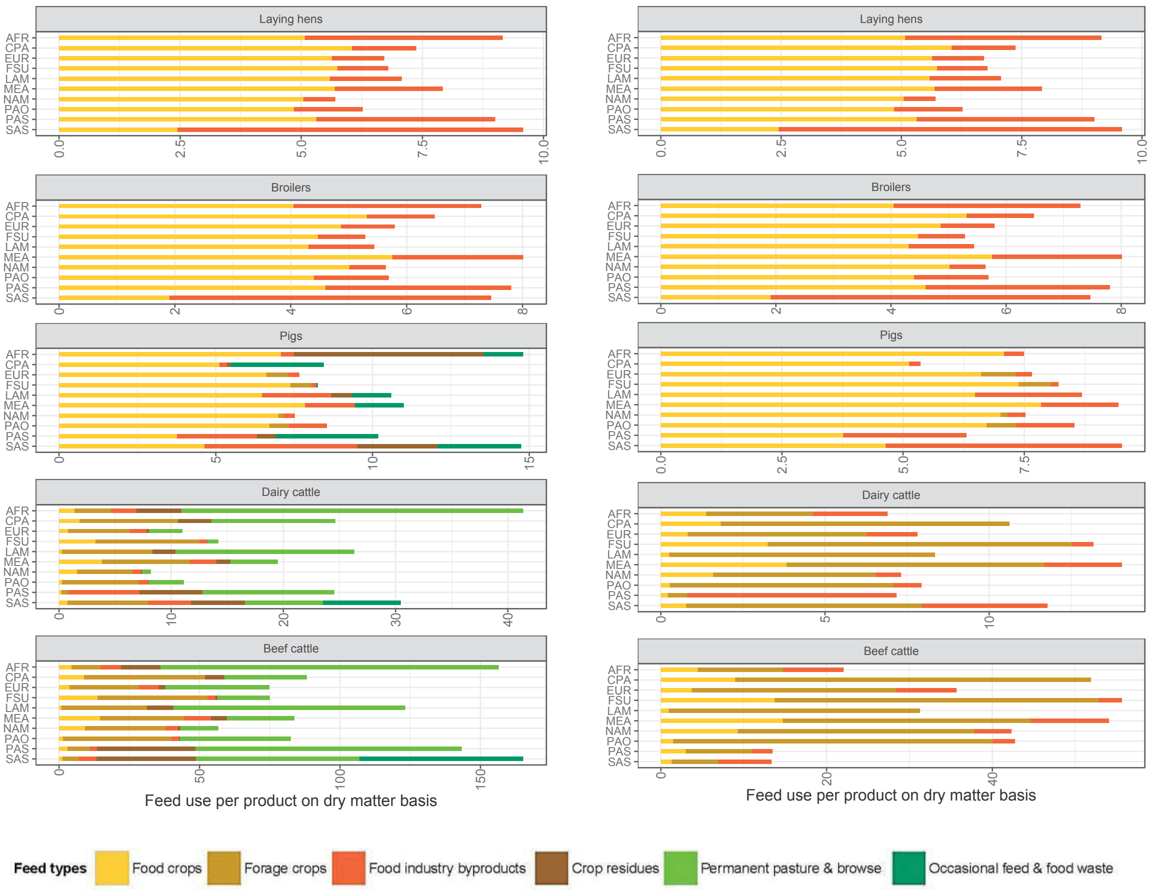

Fig. S10. Regional feed baskets (left panel) in 2050 in the BASELINE scenario for all animal food systems expressed as units of feed used to generate one unit product on dry matter basis. The right panel shows the fraction of feed baskets that is related to cropland harvest, i.e. required crop input per generated livestock product. Note that feed use includes energy requirements of all animals within the respective animal food system, i.e. reproducers, producers and replacement animals. For the dairy cattle system, product output comprises whole-milk as well as meat from milk cows (see Wirsenius (2000) for more information on herd structures).

B.3. Spatially explicit patterns of forest cover in 2050 for all scenarios

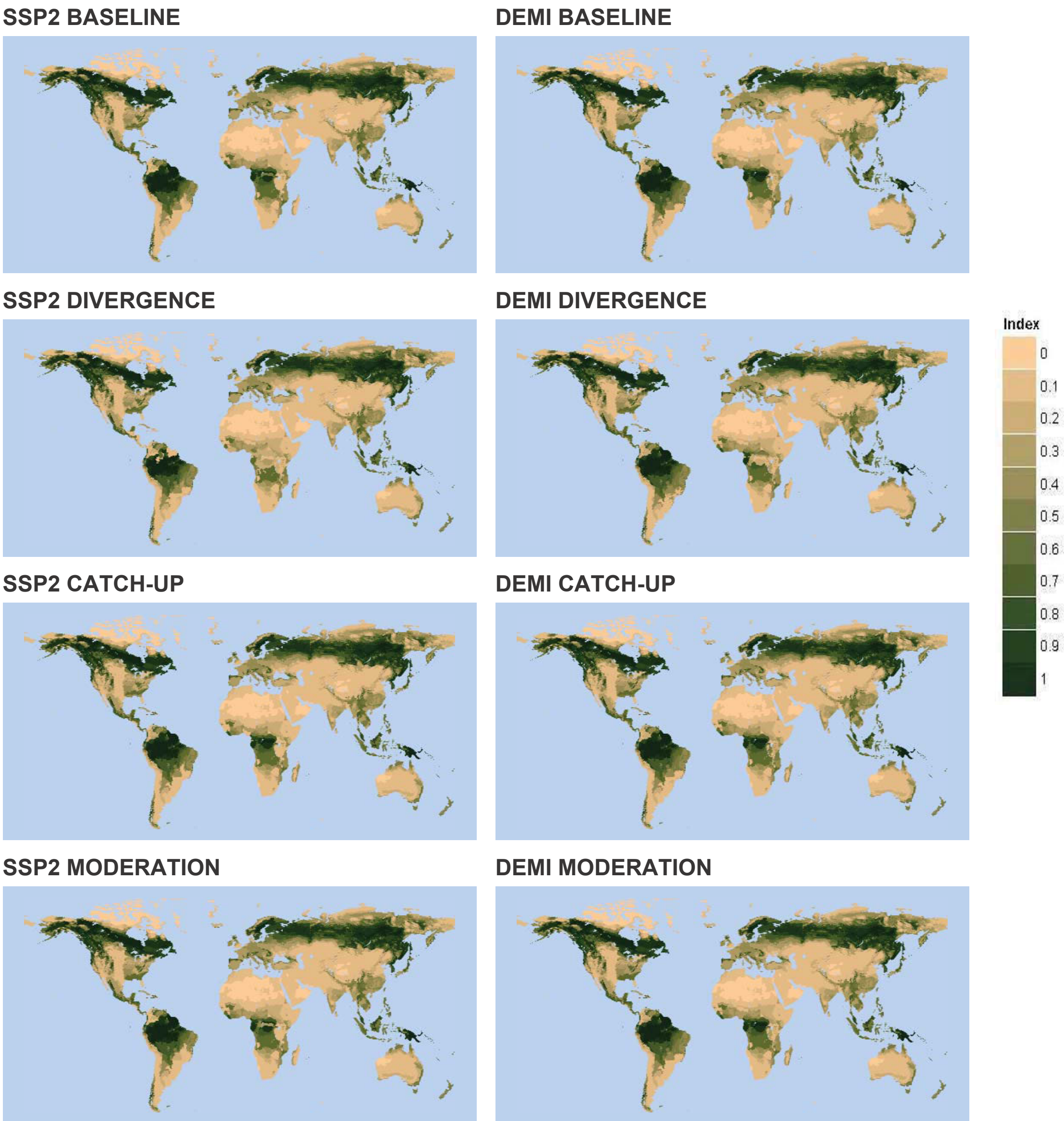

Fig. S11. Simulated spatially explicit patterns of forest cover in 2050 for all scenarios. Due to computational constraints regarding the optimisation process in MAgPIE, geographically explicit information on 0.5 degree resolution is aggregated to 1000 cluster. Colours indicate the share of the respective land type in each cluster.

B.4. Spatially explicit patterns of cropland in 2050 for all scenarios

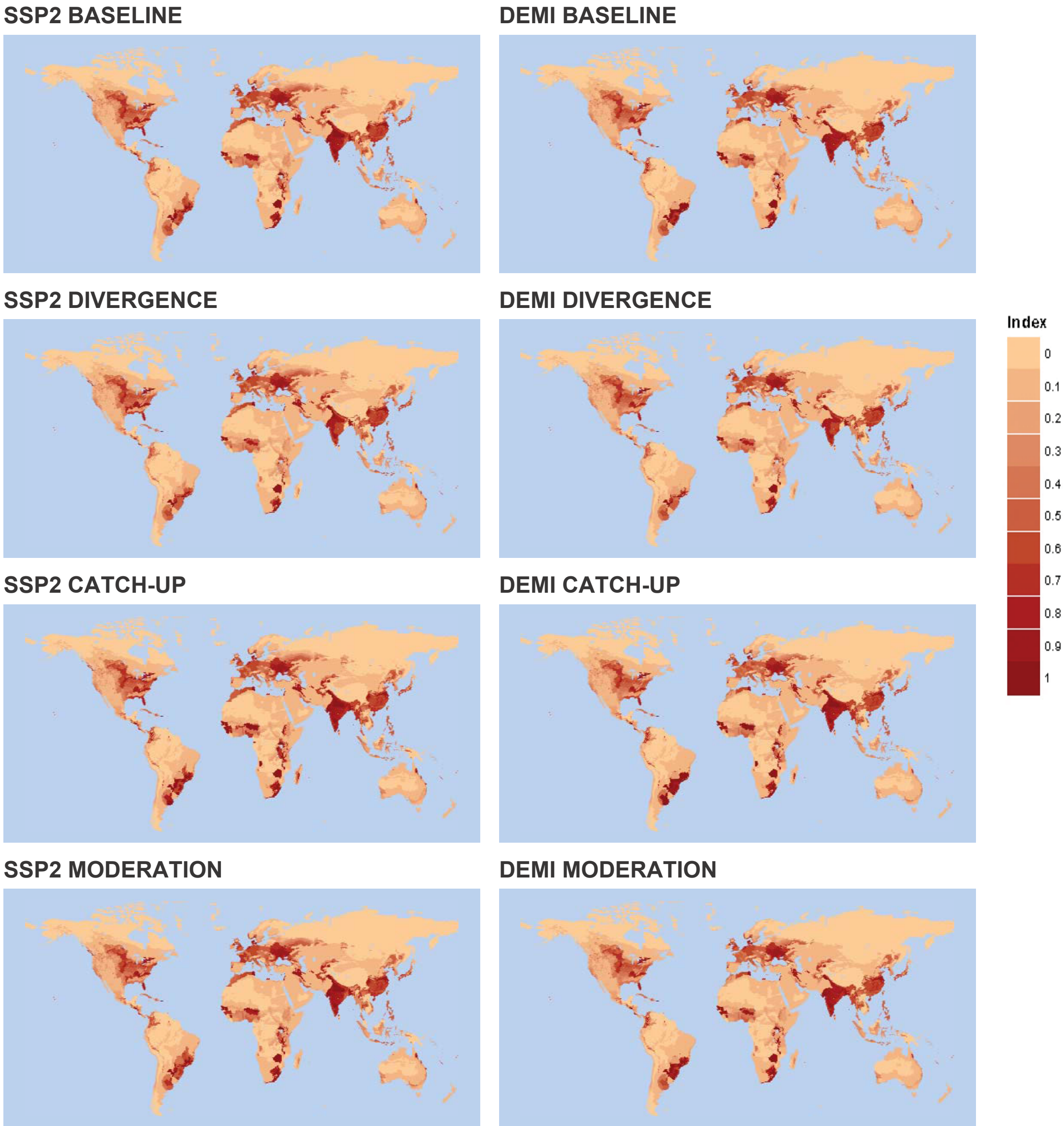

Fig. S12. Simulated spatially explicit patterns of cropland in 2050 for all scenarios. Due to computational constraints regarding the optimisation process in MAgPIE, geographically explicit information on 0.5 degree resolution is aggregated to 1000 cluster. Colours indicate the share of the respective land type in each cluster.

B.5. Spatially explicit patterns of pasture in 2050 for all scenarios

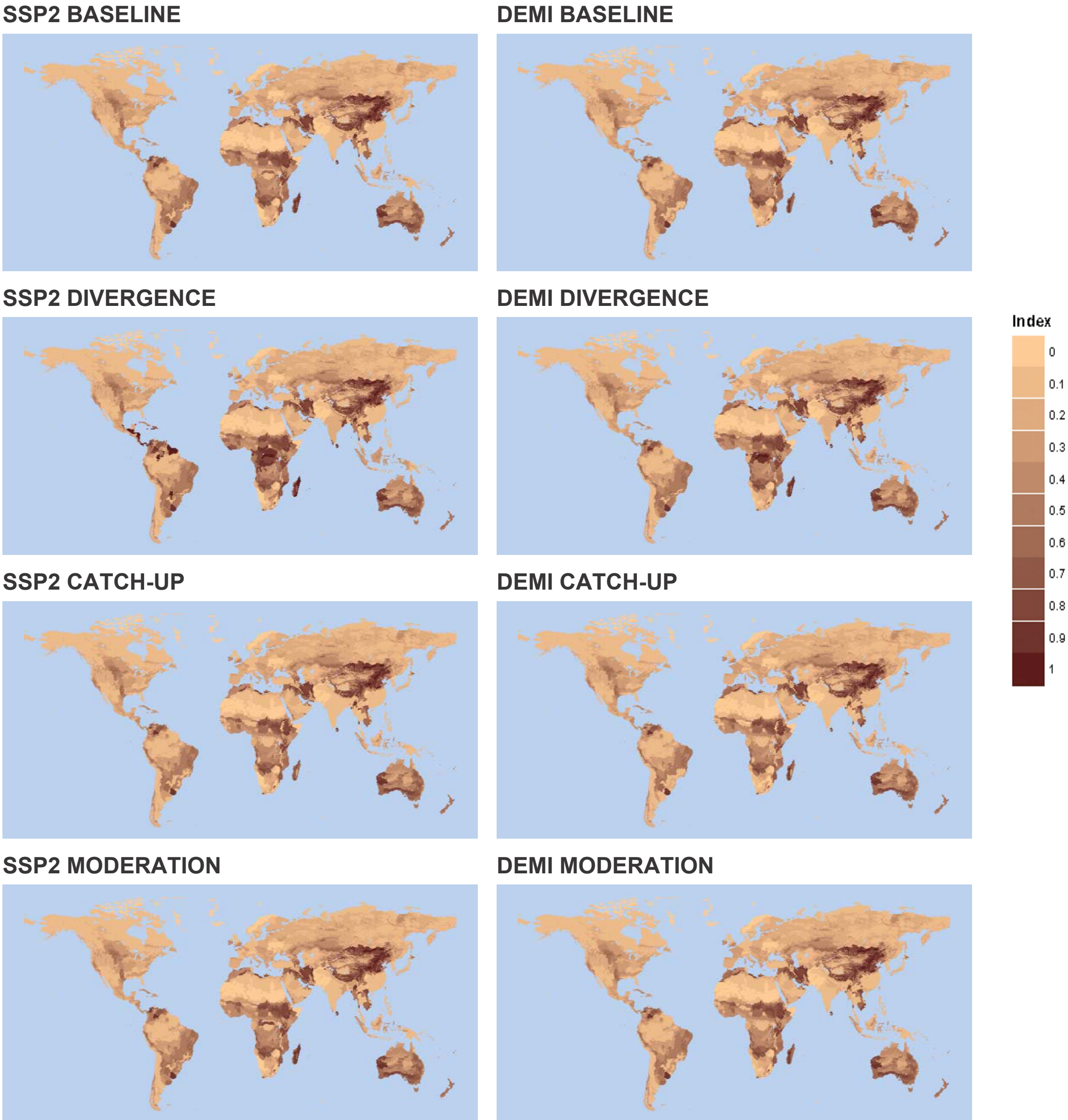

Fig. S13. Simulated spatially explicit patterns of pasture in 2050 for all scenarios. Due to computational constraints regarding the optimisation process in MAgPIE, geographically explicit information on 0.5 degree resolution is aggregated to 1000 cluster. Colours indicate the share of the respective land type in each cluster.

B.6. Global feed demand in 2050

Table S4. Global feed demand in 2050 in Mt dry matter (DM) and percentage changes between 2010 and 2050 for all scenarios. Food industry byproducts comprise oil cakes, molasses and brans and are generated in the manufacturing of harvested crops into processed food. Food waste is included in occasional feed.

	SSP2 (2050)				DEMI (2050)			
	BASELINE	DIVERGENCE	CATCH-UP	MODERATION	BASELINE	DIVERGENCE	CATCH-UP	MODERATION
Feed demand								
Food crops	1741	1610	1681	1638	1021	1030	1068	1051
Forage crops	2491	2157	2704	2480	1752	1451	1918	1720
Food industry byproducts	823	676	968	841	635	539	765	642
Crop residues	1134	1593	938	1204	852	1196	721	850
Grazed biomass	4591	6661	3984	4982	3527	4714	2730	3594
Occasional feed	1064	1412	842	1125	722	1065	673	720
Total crops	4232	3766	4385	4118	2773	2481	2986	2771
Total biomass	11880	14140	11162	12308	8533	10017	7912	8602
Changes in feed demand								
Food crops	+70%	+57%	+64%	+60%	+0%	+1%	+4%	+3%
Forage crops	+133%	+101%	+153%	+132%	+64%	+36%	+79%	+61%
Food industry byproducts	+132%	+90%	+172%	+137%	+79%	+52%	+115%	+81%
Crop residues	+19%	+67%	-2%	+26%	-11%	+25%	-24%	-11%
Grazed biomass	+16%	+69%	+1%	+26%	-11%	+19%	-31%	-9%
Occasional feed	+18%	+56%	-7%	+24%	-20%	+18%	-26%	-20%
Total crops	+102%	+80%	+109%	+97%	+32%	+18%	+43%	+32%
Total biomass	+44%	+71%	+35%	+49%	+3%	+21%	-4%	+4%

B.7. Regional demand trajectories between 1995 and 2050

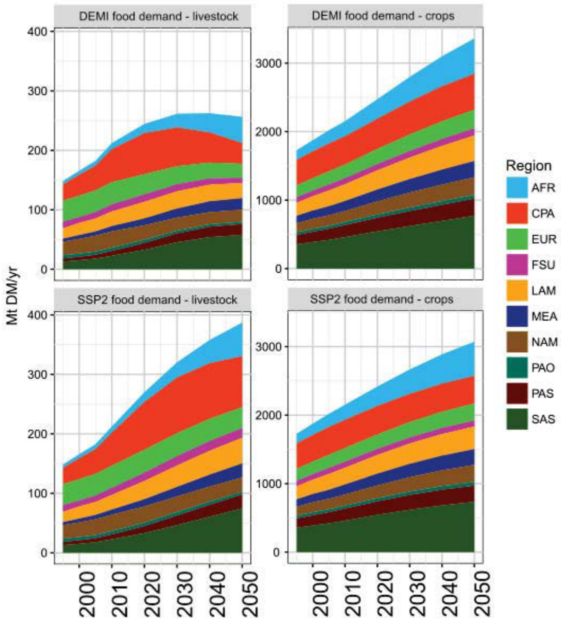

Fig. S14. Regional food demand trajectories for livestock products (left panels) and crops (right panel) between 1995 and 2050. Lower panels depict food demand projections for the SSP2 diet scenario which is calculated based on SSP2 projections on population and income trends following the methodology from Bodirsky et al. (2015). Upper panels illustrate food demand projections for the DEMI diet scenario where the share of animal-based calories (including fish) in diets is assumed to decrease in affluent regions, reaching a maximum of 15% until 2050.

B.8. Average yield increases (2010 – 2050) and livestock densities in 2050

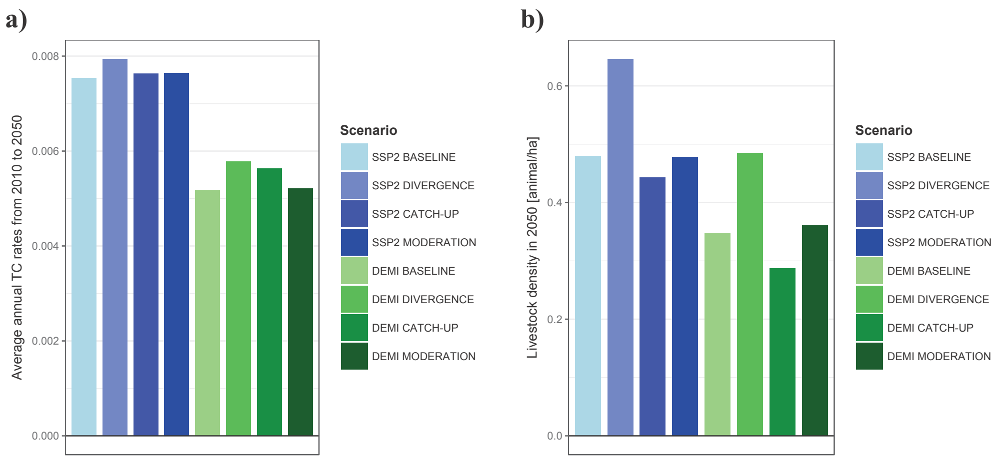

Fig. S15. Global average annual TC rates from 2010 to 2050 (a) and livestock densities in 2050 (b) for all scenarios.

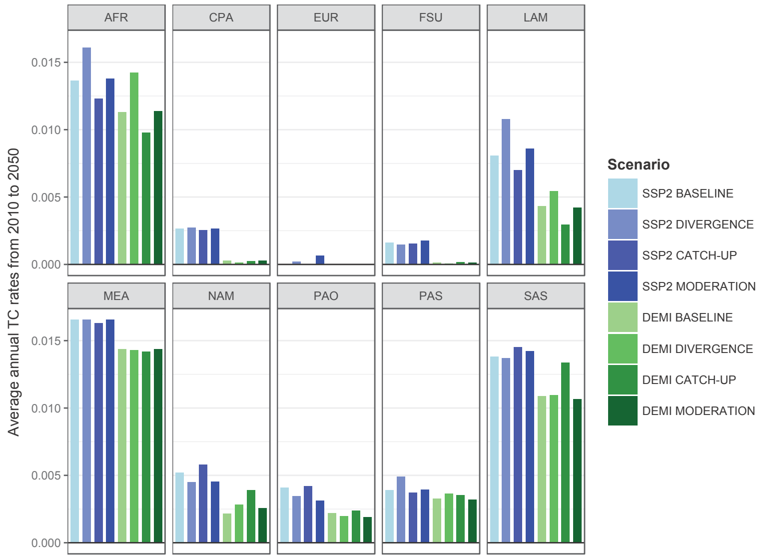

Fig. S16. Regional average annual TC rates from 2010 to 2050 for all scenarios. Rates of technological change are equivalent with associated yield increases (see Dietrich et al. (2014) for more information with regard to the relationship between TC investments and induced yield growth).

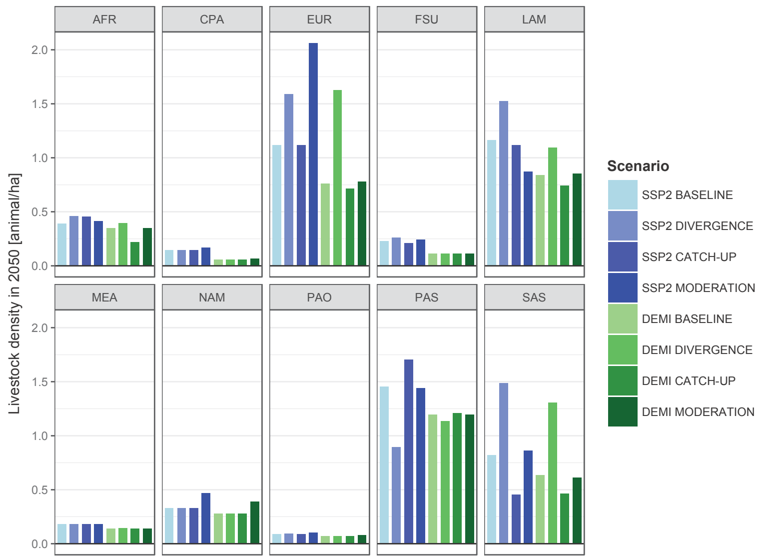

Fig. S17. Regional livestock densities in 2050 for all scenarios. Livestock density is defined as number of cattle per ha pasture for all regions (except SAS, where it is calculated as number of cattle per ha agricultural land due to the large contribution of crop residues and occasional feed to cattle feed baskets; see Wirsenius (2000) for a detailed discussion of the livestock sector in SAS).

B.9. Net trade flows between 2010 and 2050

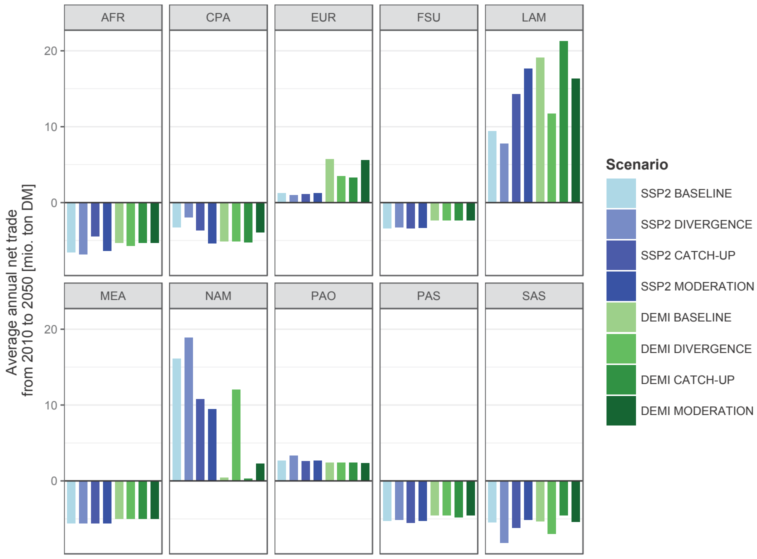

Fig. S18. Regional annual net trade of livestock products (average over the period 2010 -2050) for all scenarios in million tons dry matter. Positive values indicate net-exports, negative values net-imports.

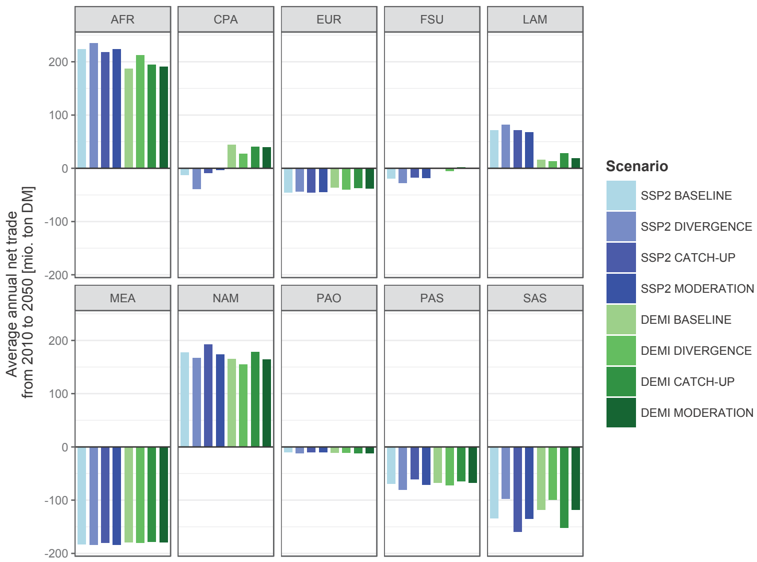

Fig. S19. Regional annual net trade of crop products (average over the period 2010 -2050) for all scenarios in million tons dry matter. Positive values indicate net-exports, negative values net-imports.

B.10. Regional development of cropland and pasture

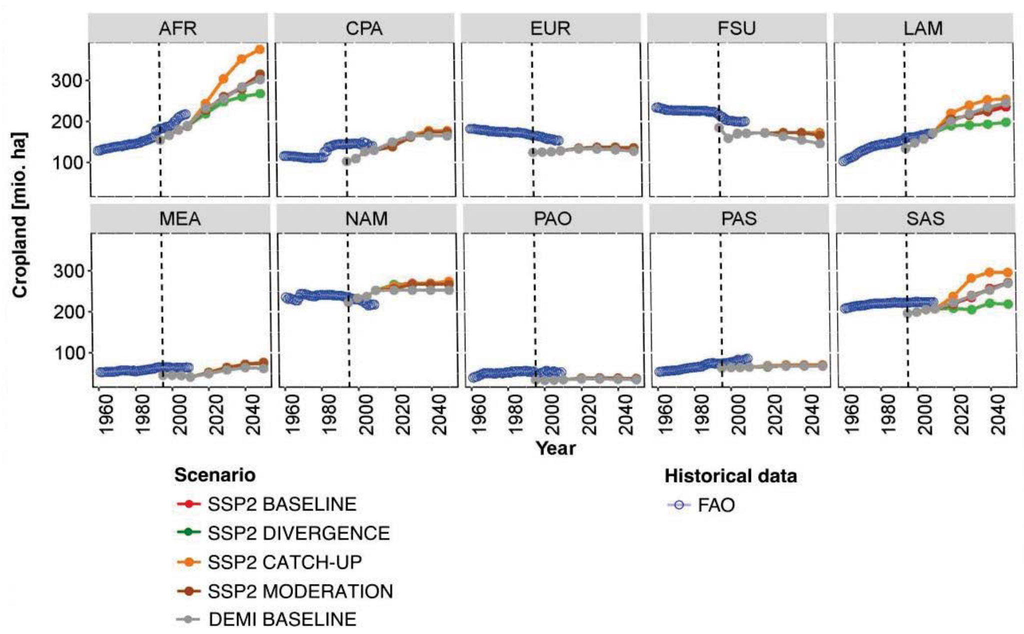

Fig. S20. Regional cropland development under four scenarios. Estimates of historical cropland by FAOSTAT (2013) (FAO, blue) for comparison. The vertical dashed line indicates the start of the simulation period.

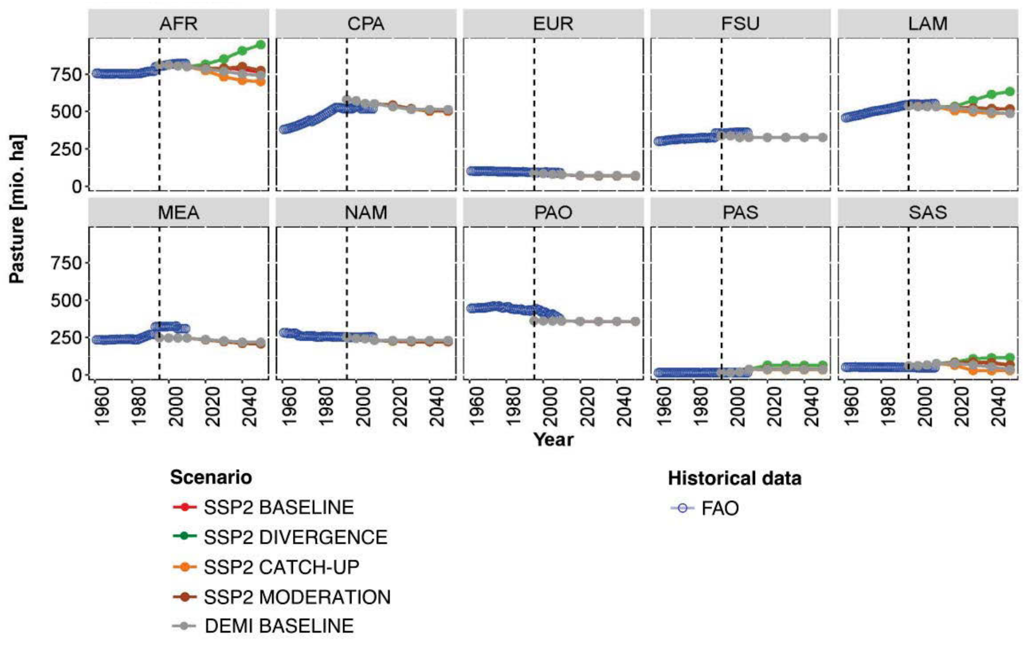

Fig. S21. Regional pasture development under four scenarios. Estimates of historical pasture by FAOSTAT (2013) (FAO, blue) for comparison. The vertical dashed line indicates the start of the simulation period.

B.11. Development of land-use intensity

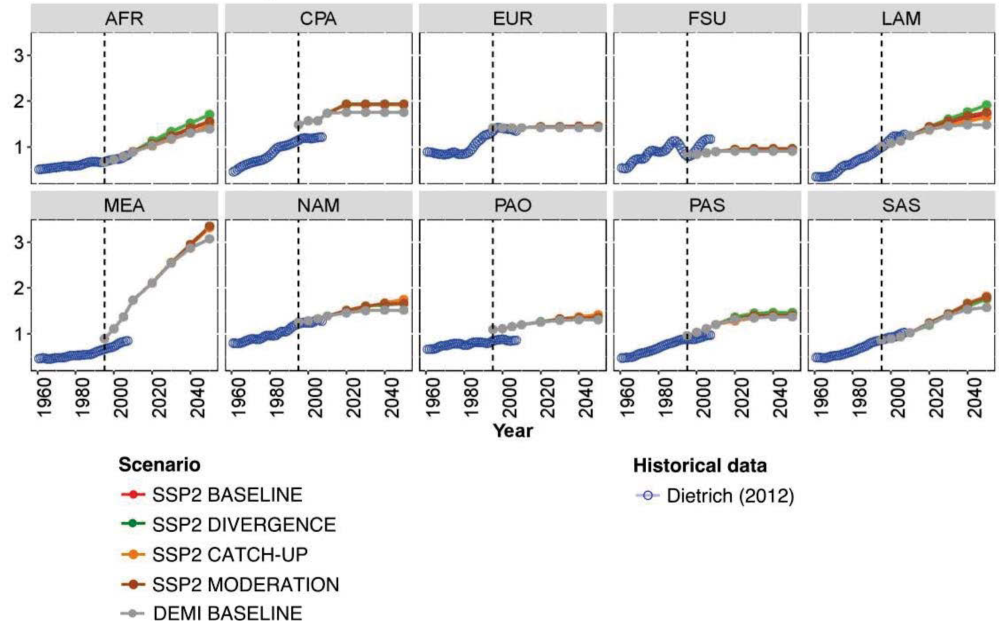

Fig. S22. Regional development of land-use intensity under four scenarios. Increases of land-use intensity are proportional to yield increases. Methodology and historical data from Dietrich et al. (2012) (see also Dietrich et al. (2014) for more information on the endogenous implementation of technological change in MAgPIE). The vertical dashed line indicates the start of the simulation period.

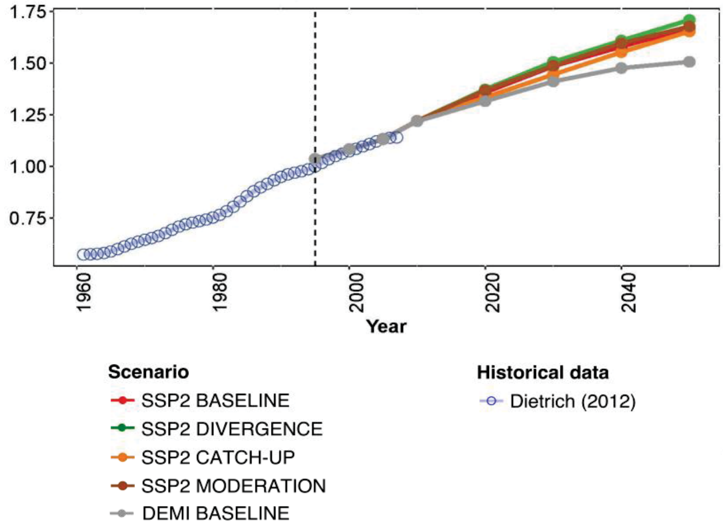

Fig. S23. Global development of land-use intensity under four scenarios. Increases of land-use intensity are proportional to yield increases. Methodology and historical data from Dietrich et al. (2012) (see also Dietrich et al. (2014) for more information on the endogenous implementation of technological change in MAgPIE). The vertical dashed line indicates the start of the simulation period.

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Chapter VI: Synthesis and Outlook

Isabelle Weindl

Contents

1. Overview

Scientific advances during the last decade deepened our understanding about the extent that livestock production contributes to major environmental problems of our time and represents an important competitor for increasingly scarce resources in many parts of the world. According to Steinfeld et al. (2006), who set the stage for numerous subsequent assessments of the livestock-environment nexus, not only the footprint of livestock production is immense and needs to be addressed with urgency, but the range and potential of sector-inherent solutions might be just as large. This doctoral thesis aims to be part of the scientific endeavour to improve the description of current environmental impacts of the livestock sector, to explore different livestock futures and their implications for the environment, and to quantify the potential of sector-specific strategies to confine the environmental burden of food production.

The analysis is guided by an overarching research question: How will future livestock production interact with the environment in the context of a changing world and how do dietary choices and transitions in livestock production systems affect agricultural resource use and environmental externalities? To address this question, the existing global land use model MAgPIE was extended by a detailed representation of the livestock sector. The integration of the livestock sector into MAgPIE, being a prerequisite and an important constituent to achieve the scientific aims of this doctoral thesis, also represents an important step of overall model improvement over the last years that contributed to several other model applications and publications, amongst others in the areas of climate change adaptation and mitigation, model intercomparison and the agricultural nitrogen cycle (Bodirsky et al., 2014; Popp et al., 2014, 2017, Stevanović et al., 2016, 2017).

Chapters II-V, representing the main part of the thesis, explored in detail different aspects of the overarching scientific objective of this thesis formulated as six specific research questions in the introductory chapter I. The following section 2 synthesizes the results of the individual studies in view of the research questions, thereby summarizing key findings of the doctoral thesis. Section 3 finally provides an outlook on future research approaches that can help to further improve livestock sector modelling and enhance our understanding of livestock-environment interactions between the poles of socio-economic developments and biophysical processes.

2. Summary and key findings

2.1. The role of transitions in livestock production systems for land use and the balance between resource requirements and availability in a changing climate

Until a few years ago, many global integrated assessments of the agricultural sector, including studies on climate change impacts, adaptation and mitigation as well as on key sustainability trade-offs either limited their scope to the crop sector or were based on highly simplified representations of animal agriculture. Similarly, early studies applying the MAgPIE model incorporated an incomplete representation of the livestock sector, accounting for three livestock activities (ruminant meat, non-ruminant meat, and milk) where both pasture area and the regional mixture of two aggregated feed categories were static over time (Lotze-Campen et al., 2008, 2010; Popp et al., 2010). An influential study published by Herrero et al. (2013) demonstrated the vast differences in feed efficiency and feed composition across livestock products, regions and production systems and called for a comprehensive incorporation of the livestock sector in sustainability studies to improve our understanding of the multiple roles of livestock for sustainably managing the world's natural resources.

Chapter II analyses the potential inherent in the current heterogeneity of livestock farming to transform biomass flows and alter agricultural resource use via changes in livestock production systems as defined by Herrero et al. (2013). Within MAgPIE, resulting changes in feed requirements are traced through the whole agricultural system, thereby simulating related changes in land use and agricultural production costs. For this study, the livestock sector in MAgPIE was extended by livestock production systems which were parametrised according to the dataset presented by Herrero et al. (2013). Transitions in livestock production systems were not only explored in view of their aptitude to improve agricultural resource efficiency and enable land sparing, but also as an option to counteract detrimental impacts of climate change on the natural resource base of livestock production. Since shifts in livestock production systems do not only influence overall resource efficiency, but also the type of biomass and land that is used to feed animals, they can take advantage of disparate climate change impacts on different crops as well as on cropland and pasture productivity.

Acknowledging the uncertainty involved in projecting climate change impacts on agriculture, the study uses climate projections for the A2 SRES scenario based on five different general circulation models (GCMs) and tests the sensitivity of results to the choice of crop growth model by using alternative crop yield simulations derived by EPIC (Izaurralde et al., 2006; Williams, 1995) and pDSSAT (Jones et al., 2003). Moreover, scenarios are calculated both with and without accounting for CO_2 fertilization, i.e. the potential of atmospheric CO_2 to stimulate net photosynthesis in C3 plants by increasing the CO_2 concentration gradient between air and the leaf interior, and improve water use efficiency of all crops and grasses due to stomatal closure.

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Transitions in livestock production systems represent a cost-effective lever to improve agricultural resource use and a low-risk adaptation strategy with various co-benefits.

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Combining information from general circulation models, global gridded crop models, and a global economic model of the agricultural sector with a detailed representation of animal agriculture, this study sheds light on the adaptive potential of structural changes in the livestock sector. It shows that independently of the choice of climate or crop model, transitions between livestock systems can alleviate climate change related costs in almost all regions and reduce agricultural land requirements. Globally, a transition towards mixed crop-livestock systems decreases adaptation costs in the agricultural sector from 3% to 0.3% of total production costs by the middle of this century and simultaneously abates tropical deforestation by 76 million ha. Due to greater input and income diversity, an integration of livestock and crop production increases resilience to climate extremes and is therefore an important target for sustainable intensification (Herrero et al., 2009, 2010; Russelle et al., 2007). In South Asia, however, results across all climate and crop models indicate that the relatively more optimistic impacts of climate change on grass yields compared with crop yields might favour grazing systems in some locations, leading to a cost reduction of 11.2%. At the global scale, a full transition to grazing systems entails, due to their on average lower feed efficiency, a strong increase in agricultural area and tropical deforestation by 185 Mha.

As the uncertainty analysis elucidates, policies supporting climate change adaptation in agriculture have to embrace a potentially wide range of future climate outcomes. In the face of these uncertainties, transitions in livestock production systems represent an effective lever to improve agricultural resource management and land sparing as well as a cost-effective and low risk adaptation strategy with various co-benefits, possibly even contributing to emission reduction. Therefore, structural changes in the livestock sector could significantly contribute to a climate-smart agriculture.

2.2. Current contribution of livestock production to agricultural resource use and environmental externalities

Recent years substantially increased our knowledge about the environmental burden and resource requirements of livestock production. Across different studies and methodological approaches, there is good agreement regarding the current contribution of livestock to agricultural biomass and land use as well as global anthropogenic GHG emissions (Bouwman et al., 2005, 2013; Davis et al., 2015; Herrero et al., 2011, 2013, 2015; Steinfeld et al., 2006; Wirsenius, 2000, 2003; Wirsenius et al., 2010). Compared to above mentioned aspects of the livestock-environment nexus, the role of livestock farming for current green and blue water consumption and agricultural nitrogen flows is less certain.

Chapter III presents a comprehensive description of the current agricultural N_r cycle, also covering N_r flows that have not been considered by previous work. For this study, MAgPIE was extended by a material flow model and an improved implementation of the livestock sector. The extended representation of feed production comprises all major feed commodities, thereby differentiating feed cultivated on cropland, biomass from pastures and various residues along the food supply chain that can be recycled as feed, such as crop residues, conversion byproducts from food processing and food waste.

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The current agricultural nitrogen cycle is highly inefficient, larger than previously estimated, and dominated by the livestock sector.

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Several new features have been introduced to the existing model, like an explicit representation of production and destinies of above and below-ground residues and conversion byproducts as well as the endogenous calculation of N_r in manure, based on N_r in feed intake and livestock productivity, and manure management. The new implementation of cropland N_r inputs includes manure, inorganic fertilizer, crop residues left in the field, atmospheric deposition, seeds, biological N_r fixation, and soil organic matter loss. To reveal N_r inefficiencies in the whole system, N_r flows are traced from N_r inputs to agricultural soils upstream through the food systems, towards food processing, the livestock sector and food intake at household level.

According to the calculations presented in chapter III, 205 TgN_r are applied to or fixed on global cropland in 1995, of which 115 TgN_r are taken up by plant biomass cultivated on cropland. Of this amount, only 12 TgN_r plant biomass is consumed by humans, while 50 TgN_r are utilized as feed, including feed and food crops, crop residues, and conversion byproducts. If supplemented by N_r flows related to grazing, 123 TgN_r enter the livestock sector as feed to produce animal products containing 8 TgN_r, of which 5 TgN_r are finally consumed.

As demonstrated by this study, the current state of the global agricultural N_r cycle is highly inefficient. Only around half of the N_r applied to cropland is taken up by plants and merely 9% of N_r appropriated in cropland biomass or by grazing is actually consumed by humans. The major inefficiency in the food system stems from the low conversion efficiency from N_r in plants to animal-based products upstream in the food supply chain in the livestock sector which, as a consequence, dominates nutrient cycling in the whole agricultural system. Since earlier studies did not cover all relevant flows of the agricultural N_r cycle, our estimate of total agricultural N_r losses (91 TgN_r) is higher than previously suggested and by far exceed the amount of 35 TgN_r proposed as planetary boundary for newly fixed nitrogen from the atmosphere (Rockström et al., 2009).

Like in the case of many agricultural N_r flows, poor data availability regarding the consumption of green (naturally infiltrated precipitation) and blue (irrigation) water in agriculture necessitates independent model assessments with different methodological approaches and parametrizations. Owing to large data requirements both regarding a detailed description of feed use and spatially explicit information about hydrological processes, estimates of water consumption attributable to livestock farming are prone to uncertainty. Due to the high biomass throughput and low resource conversion between input and product output in the livestock sector, an analysis of the livestock-water nexus offers substantial scope to identify strategies to improve total agricultural water productivity. However, few studies quantify the contribution of livestock production to agricultural green and blue water consumption at the global scale. For the study presented in chapter IV, a comprehensive representation of feed use is combined with spatially explicit data on land use and cropping patterns, area equipped for irrigation, water availability and crop water demand for rainfed and irrigated crops, derived by linking the dynamic global vegetation and hydrology model LPJmL with the economic land-use model MAgPIE.

Our findings underline the relevance of exploring links between livestock and water, with around one-third of crop water consumption in the year 2000 being attributable to feed production and similar amounts of water being consumed via grazing. The study's estimate of water consumption attributable to cropland feed production (2170 $km^3 yr^{-1}$) is higher than previously estimated. Our estimate of 7% blue water in the livestock water footprint is comparable to findings from Mekonnen and Hoekstra (2010) suggesting that 6.2% of livestock related water consumption is of blue origin.

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Water use attributable to livestock production accounts for 56% of agricultural water consumption and 38% of crop water consumption.

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Accounting for regionally diverse grazing intensities, estimates are presented for evapotranspiration related to total pasture area and water consumption related to grazing. Estimated water consumption attributable to grazing (2820 km^3yr^{-1}) is higher than previously published values, partly as a result of additional energy expenditures for grazing (increase in maintenance requirements by 10-20%), which according to NRC (1989) may reach up to 50% for grazing animals walking long distances. Estimated total evaporation on global pastures (16520 km^3yr^{-1}) resides within the considerable range (5800-20400 km^3yr^{-1}) defined by earlier studies and is comparable to 12960 km^3yr^{-1} annual evapotranspiration as suggested by Hanasaki et al. (2010) for the period 1985-1999.

Bringing together water consumed to produce feed on cropland and pastures, consumptive water use of livestock amounts to 56% of total agricultural water consumption, where precipitation water over grassland represents an important contribution to fulfil water requirements to produce livestock commodities.

2.3. The evolution of resource use and environmental impacts under different scenarios of future livestock production

Across the studies presented in chapters II, III, IV and V, this thesis develops scenarios of future livestock production and evaluates their environmental and resource implications, where special attention is given to agricultural biomass production, land use and land use change, carbon emissions from land conversion processes, green and blue water consumption, and nitrogen flows.

Future scenarios of animal agriculture have to incorporate relevant aspects of global change that will shape the livestock sector in form of demand-side (e.g. population growth, dietary transitions) and supply-side transformation processes (e.g. productivity developments, structural changes, trade, climate change impacts). To facilitate the description of different plausible worlds, the MAgPIE model includes several relevant drivers of the agricultural sector like population, dietary patterns, livestock productivity trends, manure management systems, trade regimes, and forest protection policies, which can be parametrized according to different scenario families such as the International Assessment of Agricultural Science and Technology for Development (IAASTD) (McIntyre et al., 2009) as in chapter II, the storylines of the Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000) in chapter III, or the recently designed Shared Socio-Economics Pathways (SSPs) (Kriegler et al., 2012; O'Neill et al., 2014; Popp et al., 2017) in chapters IV and V.

In chapters IV and V, eight scenarios of future livestock production are developed around the narrative of the SSP2 scenario ('Middle of the Road'), accounting for variations along the dimensions of dietary choices and livestock productivity (annual production per animal). Scenario projections describe very diverse future developments of animal farming and the whole agricultural system.

Due to the low biomass conversion efficiency of livestock production, appropriation of plant biomass in agriculture is substantially influenced by demand- and supply-side assumptions of the eight different livestock futures. In the baseline scenario, global feed demand rises from 8280 Mt DM in 2010 to 11880 Mt DM in 2050 (+44%), while at the same time production of food and forage crops increases by 84%. Across the two diet and four livestock productivity scenarios, feed demand of the global animal population changes by -4% to +71% between 2010 and 2050, being an aggregate of diverse dynamics in feed subcategories (-31% to +69% for grazed biomass, -24% to +67% for crop residues, +52% to +172% for conversion byproducts, +36% to +153% for forage crops, and 0% to +70% for food crops). As a consequence, production of both food and forage crops grows by 44-97%, harvest of food crops increases by 46-64%, and total agricultural biomass production (above-ground cropland production including residues and grazed biomass) rises by 29-62%.

Analogously, model simulations presented in chapter V indicate that future developments in the livestock sector will considerably influence land use dynamics on the global scale. In the baseline scenario, total agricultural land increases from 4630 Mha in 2010 to 4830 Mha in 2050 as a result of substantial cropland expansion and a reduction in pasture area. All investigated scenarios involve further expansion of cropland (10-35%). Only under stagnating low livestock productivities in some regions, pasture area is projected to increase, thereby significantly intensifying pressures on forests. Across all diet and productivity scenarios of chapter V, projected deforestation ranges between 70 and 360 Mha. If only considering current livestock production systems and disregarding possible productivity gains beyond shifts in regional livestock systems (chapter II), deforestation amounts to 228-488 Mha. The lower bound hereby reflects implications of slight productivity increases (shift to mixed crop-livestock systems) on land dynamics under climate change, where the upper bound is the result of a transformation towards rangeland based systems characterised by low feed efficiency and livestock productivity.

Across all scenarios of chapter V, projected expansion of agricultural land entails further losses of natural ecosystems and depletion of terrestrial carbon stocks until mid of the century, but by different orders of magnitude. Cumulative carbon emissions amount to 74-295 Gt CO_2 emitted to the atmosphere, where Sub-Saharan Africa and Latin America contribute 74-93% to global carbon losses. Stagnating productivity trends in these regions would lead to a tripling of carbon emissions compared to scenarios assuming slight productivity increases.

Findings in chapter IV emphasize that human diets and livestock productivity trends are also relevant for the magnitude of future agricultural water use and the balance between water consumption attributable to cropland and grassland, as well as between green and blue water flows. Until the middle of the century, blue water consumption grows by 30%, while green water consumption increases by 56% in the baseline scenario compared to levels in 2010. Across all diet and productivity scenarios, crop water consumption attributable to livestock production increases by 11-51% for blue and by 5-90% for green water. Resulting changes in crop water consumption of the whole agricultural sector amount to 19-36% related to blue and 26-69% related to green water flows. Evaporation over pastures changes by -13% to +16% and water consumption attributable to grazing by -41% to +48%. Accounting for grazed biomass and feed cultivated on cropland, water consumption of livestock feed production changes by -6% to +50% across all scenarios.

In chapter III, the future of the agricultural N_r cycle is investigated using the full parametrization of the SRES storylines. Consequently, the size of many N_r flows is also subject to developments outside the livestock sector, such as human population growth (between 8.6 to 10.8 million people in the mid-century) and soil N_r uptake efficiency (between 55% and 65%). However, the parametrisation of the SRES scenarios include important drivers to describe different livestock futures, like the level of livestock system intensification (between 50% and 80% of livestock production allocated to intensive systems) and the share of animal-based calories in diets (between 17% and 24%).

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Animal farming will drive future resource use in agriculture. Investigated supply- and demand-side developments in the livestock sector substantially influence agricultural biomass (29-62% increase), cropland expansion (10-35% increase), deforestation (70-360 Mha), cum. carbon emissions (74-295 Gt CO_2), N_r in manure (95-136% increase) and crop water consumption (25-64% increase).

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In all SRES scenarios including the environmentally oriented scenarios, a strong surge of the N_r cycle occurs in the first half of the 21st century, involving an increase in soil inputs from 185 TgN_r in 1995 to 286 (B2) - 412 (A1) TgN_r in 2045 and a rise in N_2O emissions from 3 Tg N_2O-N in 1995 to 7 (B1) - 9 (A2) Tg N_2O-N in 2045. The importance of the livestock sector for the throughput of N_r in the agricultural system can be deduced from the amount of N_r excreted in manure, which is endogenously determined from N_r in feed minus the amount of N_r in the slaughtered animals, milk and eggs, thus taking into account livestock productivity, feed efficiency and feed composition. N_r in manure increases from 111 TgN_r in 1995 to 217 (B1) - 262 (B2) TgN_r in 2045, which for all scenarios substantially exceeds the amount of N_r in global cropland harvest (143 - 182 TgN_r).

Summarizing results of chapters II-V, the livestock sector will continue to drive agricultural biomass appropriation, nutrient cycling in agriculture and water consumption, and shape land and carbon dynamics under a range of quite different future developments of agriculture.

2.4. Impacts of livestock productivity on the environmental footprint of agriculture

Historical developments suggest interdependencies between the rising food demand of a growing and increasingly wealthy human population and the trend towards intensification in agriculture. Over the last half century, livestock feed demand increased by 108%, arable land for feed crops by 30% and pasture by 10%, while animal calorie production more than tripled, which can mainly be attributed to improved and more resource-efficient production methods (Davis et al., 2015; Herrero et al., 2010; Steinfeld and Gerber, 2010). In consequence, the environmental burden of future livestock production is likely to be subject to innovation, productivity increases and management practices. To facilitate the analysis of the role of productivity gains in the livestock sector for resource use and the environmental footprint of agriculture, this thesis proceeds in two steps:

Firstly, acknowledging the current heterogeneity of livestock production systems, chapter II investigates resource implications of a shift in regional livestock production systems, involving changes in productivity, feed efficiency and feed composition. For this aim, the simplistic representation of livestock production in the early phase of MAgPIE model development was replaced by the detailed dataset on livestock production systems by Herrero et al. (2013). Chapter II highlights the magnitude of differences in land use dynamics and especially deforestation until 2050 (228-488 Mha) stemming from variations in current livestock production systems. However, transitions between today's regional systems are unlikely to be sufficient to describe the full range of possible productivity gains in the next decades, since livestock productivities of the same production system and agroecological zone strongly vary across regions. Moreover, historical developments in some places demonstrate the large magnitude of possible productivity gains even within one or two decades (e.g. in China for beef production).

In a second step, a comprehensive method was therefore developed to understand the relationship between livestock productivity, feed efficiency and feed composition. This method is used to design alternative livestock futures consistent with both historical livestock productivity developments and scenario storylines (see chapters IV and V). The non-linear regression models for feed composition incorporate spatial heterogeneity by considering Koeppen-Geiger climate zones. The type of biomass used to feed animals is only to a certain extent influenced by universal aspects (e.g. the need for more energy-rich feed at higher productivity levels), whereas other aspects are influenced by site-specific conditions (e.g. quality and availability of grasslands for grazing; agroecological and climatic conditions that favour selected feed items). From the analysis follows that intensification of livestock systems does not only improve feed conversion, but also entails a transition from residues, food waste and grazed biomass to higher quality and nutrient-rich feed, where the curve describing this transition varies across aggregated climate zones. Within the integrated modelling framework of MAgPIE, the implications of the interplay between improved feed efficiency and the growing importance of high quality feed from cropland at the extent of grazing and various residues along the food supply chain are explored with regard to water resources in chapter IV and with regard to land and carbon dynamics in chapter V.

Model simulations indicate that increasing livestock productivity is a driver of cropland expansion, where consequences for forests and other natural ecosystems depend on the concurrent reduction in pastures and the suitability of these areas for cropping. Already minor productivity gains in extensive livestock production systems can halve deforestation and carbon emissions, since decreases in pasture area occur faster than expansion of cropland. Trade-offs with soil carbon losses due to pasture-to-cropland conversion are more than compensated by substantially lower emissions from vegetation carbon stored in native forests. However, if further proceeding to high productivity levels, large-scale pasture-to-cropland conversion involves substantial depletion of soil carbon stocks, possibly leading to a net increase of carbon emissions, although total feed demand and deforestation are slightly reduced.

With regard to water, livestock productivity determines not only total agricultural water use, but also the balance between water consumption attributable to cropland and grassland, as well as between green and blue flows. Assuming continuously low productivity in some regions, high total water requirements per livestock product in extensive systems are fulfilled by unlocking additional green water resources through expansion of pastures. In contrast, productivity increases in extensive systems involve a shift from grassland/green water resources to cropland/ blue water resources. Although increases in livestock productivity are beneficial regarding green water consumption, they increase blue water use which may jeopardize human water security and environmental flow requirements of aquatic ecosystems.

Since green water resources are essentially tied to land, the trade-off between green and blue water use in livestock production is essentially a trade-off between aquatic and terrestrial ecosystems. If further accounting for increases in the cropland N_r budget in the wake of livestock system intensification (chapter III), productivity gains in livestock production also involve trade-offs between carbon and nitrogen losses. How to solve these trade-offs and sustainability dilemmas related to livestock productivity depends on site-specific conditions (e.g. the availability of blue water) and the existence of environmental policies that e.g. could trigger improvements of irrigation efficiency and reallocate crop production to areas where green or blue water resources are abundant. Another promising option to reduce the described sustainability trade-offs is to loosen the link between livestock productivity and cropland feed demand, e.g. by improving quality and availability of non-cropland or by-product feed components, e.g. through dual purpose food/feed crops (Blümmel et al., 2009).

Furthermore, several studies indicate that highly intensive large-scale livestock operations might cause pollution and health risks through nitrogen, pesticides, pathogens, antibiotics and involve conflicts with animal welfare and the loss of biodiversity (Franzluebbers et al., 2014; Lemaire et al., 2014; Russelle et al., 2007; Tilman et al., 2002). As our model simulations show, moderate productivity reductions in very intensive systems have only minor and moreover ambiguous effects on agricultural water consumption, land dynamics and carbon emissions. Thus, attempts aimed at abating side-effects of industrial livestock production that might moderately impede productivity could be successful without negative consequences regarding water, land and carbon.

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The potential of livestock productivity gains to mitigate deforestation and carbon emissions is large. However, productivity growth in the livestock sector involves trade-offs between aquatic and terrestrial ecosystems, and between nitrogen losses and carbon emissions.

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2.5. The potential of dietary choices to attenuate environmental externalities of food production

There are large differences in the level of per-capita livestock consumption between countries, mainly due to economic drivers such as income, but also shaped by cultural factors, urbanization and changing lifestyles (Bodirsky et al., 2015; Drewnowski and Popkin, 1997; Steinfeld et al., 2006). The unfolding of the livestock revolution in developing countries will narrow this gap and contribute to food security (Herrero et al., 2009). While still 795 million people are suffering from hunger and undernourishment (FAO, 2015), unbalanced diets and overconsumption cause many health problems in affluent regions (Springmann et al., 2016). Environmental and ethical concerns could lead, however, to a reduction in the consumption of livestock products in developed regions (Fox and Ward, 2008).

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Dietary changes can substantially abate deforestation and carbon emissions, whereas direct positive effects on blue water use are small and prone to uncertainty.

Moreover, changing diets increase the option space to solve sustainability trade-offs between land and water resources.

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In the last decade, demand-side oriented strategies aimed at the decline in livestock consumption in affluent societies have climbed up the scientific agenda as an option to attenuate several environmental externalities of livestock production with synergies in the area of public health (Bodirsky et al., 2014; Jalava et al., 2014; Springmann et al., 2016; Stehfest et al., 2009; Stevanović et al., 2017). There is evidence that changes in dietary preferences might even be more effective than technological mitigation options and have a similar GHG mitigation potential as an agricultural GHG tax policy, but without negatively impacting on food prices which could deteriorate food security in developing regions (Havlík et al., 2014; Popp et al., 2010; Stevanović et al., 2017).

Chapters IV and V explore the potential of dietary changes in affluent regions to reduce environmental externalities of food production under different livestock productivity pathways. Transitions in dietary patterns towards a maximum of 15% animal-based calories in diets until 2050 can reduce cropland expansion by 23-39%, abate deforestation by 47-55% and mitigate cumulative carbon losses by 34-57%, depending on the livestock productivity scenario (chapter V). The resulting annual carbon mitigation potential is in the range of 1.1 - 4.2 Gt CO_2/yr for the default model setting. Accounting also for alternative developments of crop productivity, pasture management and trade regimes, the spread of our estimates amounts to 0.9 - 6.5 Gt CO_2/yr. This finding indicates a strong dependence of climate benefits of changing consumer preferences on interactions of productivity trends in the crop and livestock sector, as well as on economic processes. Highest emission abatement (63-78%) can be attained if dietary changes are combined with sustained efforts to improve productivity in plant production.

Chapter IV shows that dietary changes can substantially attenuate agricultural water consumption, but mainly of green origin. The higher sensitivity of rainfed agriculture to lower consumption of animal-based commodities suggests that it is primarily land which is spared and only secondarily freshwater. Already today, deployment of irrigation is limited by water availability and below optimum regarding economic and agronomic considerations in many locations. The sensitivity analysis in chapter IV indicates that direct positive effects of changing diets on blue water are highly uncertain and subject to the interplay of biophysical and socio-economic processes, e.g. economic competitiveness of irrigation activities and establishment of irrigation infrastructure compared to cropland expansion and R&D investments in the crop sector under given availability of land and water resources.

Across all investigated scenarios, the most optimistic projection of freshwater use in agriculture still represents a 19% increase compared to current levels. Accordingly, dietary changes cannot solve the water challenge of future food supply without dedicated water protection policies such as water rights cap-and-trade schemes and water pricing.

Our findings of chapters IV and V highlight the non-linearity of systems' responses to demand- and supply side changes in agricultural production and the outstanding importance of economic processes for sustainability assessments. Furthermore, the scenario matrix along the two dimensions of diets and livestock productivity reveals that already the investigated modest reduction in livestock consumption can blur differences between environmental impacts of the different livestock productivity pathways. Regarding carbon emissions, dietary changes reduce the spread of carbon emissions from 125-295 Gt CO_2 to 74-127 Gt CO_2. Thus, environmental impacts of single drivers of the agricultural sector depend on the whole socio-economic context and the pressure from food demand.

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Pastures are an important resource for agriculture and focal point of land conversion processes. Grazing involves trade-offs that depend on pasture management, evolve with livestock productivity gains, and are attenuated with reduced consumption of livestock products.

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Dietary changes could therefore enlarge the option space to solve sustainability trade-offs involved in livestock productivity gains, amongst others between land and water, and to develop regional livestock systems according to site-specific conditions and also in view of ethical considerations regarding animal welfare, thereby progressing from a "land and carbon-only" focus to a more inclusive approach to sustainability.

2.6. The role of pastures for sustainable livestock futures

Pastures are an important resource for livestock production, contribution 48% to global dry matter feed demand (chapter V). Although extensive systems will be of minor importance to increase the supply of livestock products for a growing market, grazed biomass will still account for 35-47% across all productivity scenarios investigated in chapters IV and V. Area requirements involved in grazing are substantial, accounting for 26 percent of the ice-free terrestrial surface of the planet (Steinfeld et al., 2006). Despite the increasing demand for animal-based products, pasture area is projected to increase only under the assumptions of continuously low livestock productivities in regions with extensive livestock production (chapter V) or that productivity increases are confined to transitions between current regional systems (chapter II).

Our results highlight the pivotal role of pastures for land conversion processes. Under the given major socio-economic trends driving growth in food demand, expansion of pastures significantly intensifies pressures on terrestrial ecosystems and causes deforestation. On the other hand, pastures represent an important land resource that can be used for the cultivation of crops. Chapter V highlights the potential of pasture-to-cropland conversion processes to divert pressures from pristine forests and other natural ecosystems, which challenge the perception that the vast land areas required for grazing have little ecological opportunity costs (Bradford, 1999).

Pastures are not only from the land but also from the water perspective an important resource, where conversion of pastures to cropland extends the water budget to produce food without further increasing water withdrawals for irrigation. Thus, the relevance of water consumption on grazing land depends on the opportunity costs of involved precipitation water (and land) for the crop sector, since impacts of grazing on the hydrological cycle are relatively small (Peden et al., 2007; Steinfeld et al., 2006). However, pasture-to-cropland conversion is also critical from the perspective of maintaining ecosystem services, biodiversity (Alkemade et al., 2013) and carbon sequestration (Conant et al., 2001; Don et al., 2011; Popp et al., 2014) on agricultural land, and is likely to affect hydrological processes through e.g. higher run-off from cropland (Peden et al., 2007). Moreover, pastures require little additional input like irrigation and fertilization beyond N_r excreted from grazing animals, whereas additional cropland increases N_r fixation and the agricultural N_r cycle (chapter III).

However, the potential of pastures to sustain crucial ecosystem services on agricultural land regarding hydrological processes, carbon sequestration and biodiversity depends on their management. Non-optimal stocking rates, excessive removal of biomass and other poor grazing management practices have led to degradation and the depletion of soil carbon stocks (Conant et al., 2001; Herrero et al., 2016; Ojima et al., 1993), while good management can improve net primary productivity and soil carbon content (Conant and Paustian, 2002). Instead of being intrinsically critical, appropriate grazing is increasingly regarded as prerequisite to the conservation of rangelands (Lambin et al., 2001; Oba et al., 2000).

Chapter V analyses trade-offs between the aptitude of pasture-to-cropland conversion to avoid deforestation and related downsides arising from impaired soil carbon sequestration on agricultural land. For small to medium productivity increases, benefits from avoided deforestation significantly outperform drawbacks in terms of reduced soil carbon sequestration in pastures, since abated losses in vegetation carbon stored in forests are much higher than soil carbon losses from converted pastures. However, ambitious livestock productivity gains trigger pasture conversion and depletion of soil carbon stocks of a magnitude that cannot be counterbalanced anymore by feed efficiency gains and avoided deforestation. This finding can be explained by the interplay of the feed efficiency curves that involve a saturation of feed efficiency gains with increasing productivity, the curves reflecting the shift from grazed biomass to higher quality feed and the relative size of soil and vegetation carbon pools.

The role of pastures to produce livestock feed involves vital trade-offs between land and water, carbon and nitrogen that evolve with increasing livestock productivity and are alleviated with decreasing consumption of livestock products. Other ways out of the grazing dilemma, described by vast land requirements and little pressures on other resources, are measures to improve feed quality and livestock productivity beyond increasing the contribution of cropland-related feed per unit livestock product. Promising approaches to increase land and livestock productivity without amplifying the hunger for cropland consists in improved grassland management, e.g. by using deep-rooted pastures such as Brachiaria spp. (Thornton and Herrero, 2010), and in the adoption of silviopastoral systems (Broom et al., 2013; Thornton and Herrero, 2010), that simultaneously increase primary production as well as the nutritive quality of biomass.

Efforts to increase productivity in livestock systems with a large contribution of grazed biomass in total feed use are also important in view of the relatively more positive impacts of climate change on pasture productivity compared with crop yields, favoring grazing systems in some regions (chapter II). Moreover, rangeland-based livestock production could be a more drought-resilient option for sustaining agricultural production in areas where rain-fed cropping becomes economically infeasible due to rising temperatures or declining precipitation (Jones and Thornton, 2009).

Across all studies presented in the main part of the thesis, pasture dynamics shape land conversion processes and are a focal point of the balance between resources and environmental externalities. Grassland management affects local carbon fluxes and water flows, that have large-scale implications due to the magnitude of involved areas. The overall footprint of grazing activities is still very uncertain, but likely to contribute a noteworthy part to global environmental change. An integrated assessment of feedbacks between pasture management and biogeochemical cycles in the context of major drivers and developments of the agricultural sector is urgently needed.

3. The future of modelling livestock futures

The final section of this doctoral thesis develops a vision of future research on the sustainability of livestock production in the context of the major challenges that global change processes pose for agriculture. The growing demand for agricultural biomass for food and feed as well as for materials and bioenergy in the wake of a rising bioeconomy, and climate change impacts and mitigation, that will both intensify pressures on land use systems, need to be reconciled with conservation needs and the 'safe operating space for humanity' (Rockström et al., 2009).

As demonstrated by this thesis, future livestock production will substantially influence agricultural resource requirements to produce food, contribute to several critical externalities of agriculture and shape resource conflicts and sustainability trade-offs. Consequently, a comprehensive representation of livestock production within integrated frameworks used in sustainability research is a prerequisite to project plausible long-term developments, to identify hot-spots of resource competition and environmental degradation, and tap the full potential inherent in the livestock sector to transform material flows and resource requirements.

To this aim, future research and model development need to address areas, where uncertainty as well as potential impacts of parameters and processes on the whole system are high, as demonstrated in the thesis e.g. regarding the role of grazing and pasture management for sustainable food production. A second promising avenue of future research is to endogenise the scenario parameters, whose implications for agricultural resource requirements have been substantiated across all studies of the thesis. This would allow for better representing the option space of the coupled human-natural system to respond to global change processes, especially if analyzing future developments that exhibit large pressures on terrestrial ecosystems like broad-scale bioenergy plantations or afforestation projects e.g. on pastures. A third pillar of model development could continue the way that resulted in the emergence of spatially explicit land use models. Bringing animals on the land within a spatially explicit framework of livestock modelling would improve existing model processes and enable the spatially explicit simulation of environmental externalities like N_r pollution.

3.1. Integration of pasture management

Livestock grazing pertains to vast grassland areas, whose management affects water and carbon fluxes and land productivity of primary and secondary production. While good management can improve carbon sequestration and contribute to conservation of rangelands (Herrero et al., 2013; Lambin et al., 2001), pasture expansion and overgrazing are an important cause of ecosystem degradation and the occurrence of three critical syndromes related to grazing: desertification, woody encroachment, and deforestation (Asner et al., 2004). Despite their importance, grassland management and degradation are not only omitted in global economic land use models, but also widely disregarded by global dynamic vegetation or carbon cycle models.

Recently, grazing management was introduced into the dynamic global vegetation model (DGVM) ORCHIDEE (Organizing Carbon and Hydrology in the Dynamic Ecosystems model) at the European scale (Chang et al., 2013). The default model version of LPJmL, the global DGVM that is developed and managed at PIK and applied to provide important biophysical and spatial explicit input data for MAgPIE, includes a representation of managed grassland that does not take into account regionally varying grazing intensities and management practices (Bondeau et al., 2007). However, recent advances in model development extended the implementation of managed grasslands in LPJmL by an explicit representation of four different management options. A detailed description of the model implementation, validation of results and a first global application (figure 1) are part of a study that is currently under review (Rolinski et al., 2017).

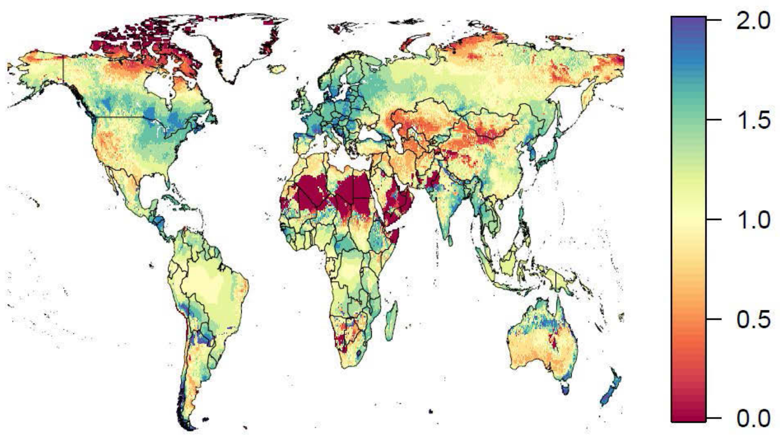

Figure 1. Distribution of livestock densities that result in maximum harvest (LSU_{max} in LSU ha^{-1}) with harvest option G_D averaged over the years 1998 to 2002. Source: Rolinski et al., 2017.

Results based on the extended model version reveal and quantify non-linear and ambiguous responses of net primary productivity and soil carbon sequestration to grazing at different stocking rates, which depend on climatic conditions and can exhibit positive feedbacks if livestock densities are well adapted to local conditions. This new implementation does not only allow for a better quantification of the human influence on the global terrestrial carbon budget, but could also be used to derive a new set of input data for MAgPIE. Based on data on the global distribution of different pasture management practices and grazing intensities, LPJmL could provide new spatially explicit input data comprising pasture productivity and carbon densities that would improve their representation in MAgPIE.

Moreover, the new implementation in LPJmL could also be applied to design exogenous scenarios of grazing management. Simulations under a discrete range of livestock densities could be used to derive a new set of input data for MAgPIE that includes the dependence of pasture productivity and carbon density from stocking rates. A promising application of this feature in MAgPIE could be to quantify implications of different stocking rates for land and carbon dynamics as emerging properties of the whole agricultural system. In such an extended modelling framework, direct feedbacks of varying grazing intensities on local carbon storage can create synergies or trade-offs with global terrestrial carbon storage due to secondary effects on land requirements and shifting land-use patterns in the context of broad-scale developments in the agricultural sector.

3.2. Endogenous transformation of the livestock sector

Agricultural production takes place between the poles of socio-economic and biophysical processes. Chapters IV and V of this thesis have demonstrated the importance of economic mechanisms for assessing implications of dietary choices and livestock management on several environmental impacts of food production. Changes in comparative advantages of regional livestock systems modify trade flows and lead to a reallocation of livestock production. Resulting regional balances between resource requirements and availability have repercussions on investments into improved management and innovation in the crop sector. While MAgPIE already includes many important feedbacks that are based on economic processes, both demand for animal-based products and livestock productivity trends are exogenously prescribed. In the context of this thesis, they are used as central scenario parameters to investigate environmental implications of a broad range of possible livestock futures.

However, if progressing from impact assessment to an analysis of suitable policy instruments to effectively abate critical environmental problems, demand- and supply-side options to shape the development of livestock production need to be price-elastic. An endogenous implementation of livestock system transitions and related livestock productivity trends would allow for modelling structural changes in the livestock sector in response of increasing scarcity of natural resources and economic incentives e.g. in the framework of emission trading or water rights cap-and-trade schemes. To this aim, data on production costs related to different livestock productivity levels as well as on investments in agricultural research and development with a livestock sector focus must be collected to establish robust relationships between livestock productivity, investments and costs based on reliable data with broad geographic coverage.

Besides being a prerequisite of evaluating a wide range of environmental taxes targeting the livestock sector, an endogenous representation of livestock dynamics could also improve standard model projections in regions that are characterised by low productive systems and strong population growth. As has been observed in the past, rising food demand and resulting resource scarcity could in turn feed back on management intensity and efforts to invest into productivity gains and technological innovation (Davis et al., 2015; Steinfeld et al., 2006; Steinfeld and Gerber, 2010). Analogously, also modelling possible futures that involve high non-food biomass demand requires model-internal feedbacks between the type of biomass, which is required e.g. for bioenergy or manufacturing in the bioeconomy, and livestock production systems. Realizing the land saving potential of endogenous structural changes in the livestock sector is of great importance for assessing climate mitigation scenarios, since the feasibility of the 2°C target depends on the availability of land-intensive terrestrial carbon dioxide removal strategies, such as bioenergy with carbon capture and storage or afforestation (Edenhofer et al., 2014; Kriegler et al., 2014).

On the other hand, different developments of the agricultural sector can have repercussions on food demand (Valin et al., 2014). The protection of pristine forest ecosystems, adoption of low-emission practices in agriculture, or large-scale afforestation projects increase agricultural production costs, land scarcity and consequently food prices (Kreidenweis et al., 2016; Stevanović et al., 2017). As food consumption patterns are influenced by a wide range of different drivers such as demography, socio-economic status, urbanization, globalization, marketing, geography, religion, culture and consumer attitudes (Kearney, 2010), price-elasticities of total calorie demand as well as the share of animal-based calories in diets play a minor role for long-term demand projections and are mainly relevant for low-income countries. Elasticities for single products are typically higher and might have an effect on the balance of land-intensive ruminant versus more efficient monogastric production systems. The income-elasticity of food and livestock demand is already incorporated in the exogenous MAgPIE food demand calculations (Bodirsky et al., 2014, 2015), which can also reproduce the trend of a falling share of animal-based products that can be observed in developed regions and might be attributable to higher health consciousness or to alternative lifestyles (Cirera and Masset, 2010). The next step in model development is to account for the income effect of increasing food prices that in turn feeds back on total calorie and animal calorie demand, thereby endogenously simulating responses of food demand to increasing scarcity.

3.3. Livestock on the land: a spatially explicit global model of livestock production

While global assessments are important to discern the whole picture and to reveal broad-scale trends and feedbacks between socio-economic drivers and resources, they are intrinsically linked to dynamics at the local scale (Verburg et al., 2016). Many process-based vegetation and crop models bridge the large gap between the global scope and local realities by applying point models on a high resolution grid based on large data sets with global coverage. The model zoo focusing on livestock is vast and diverse, reaching from thermal balance models of single animals, over barn and whole farm models to regional and global economic models (Leclère and Havlík, 2016). Although several global economic models like MAgPIE exhibit a spatially explicit representation of land and are linked to global gridded crop models to integrate biophysical information into the economic decision process, mass flows related to livestock production are typically aggregated to the level of socio-economic regions.

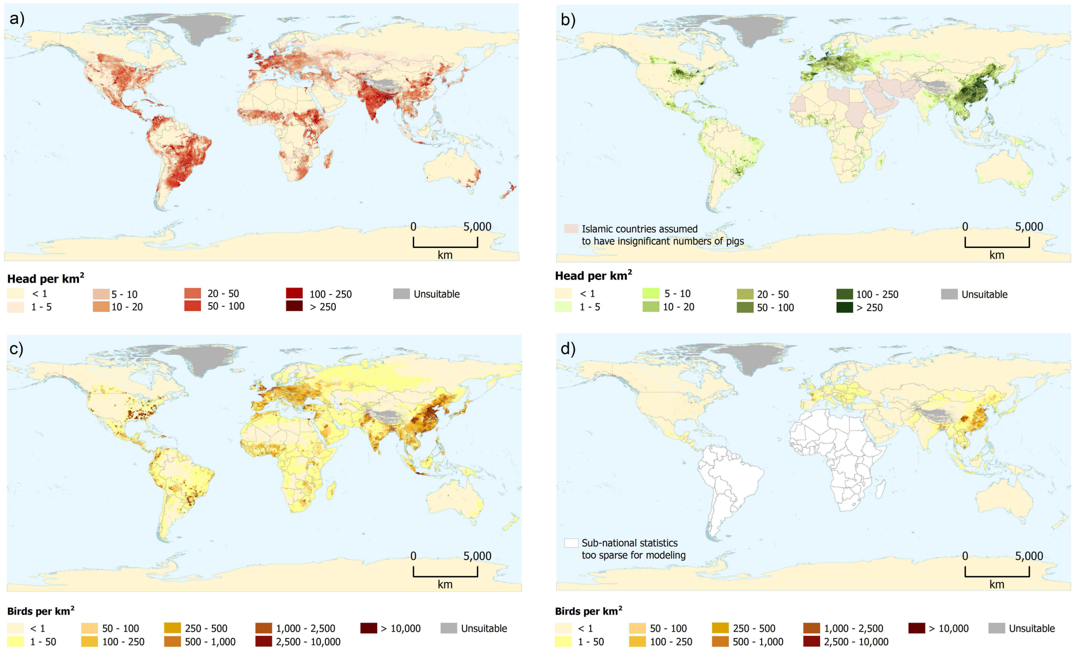

Figure 2. GLW2 global distributions of a) cattle; b) pigs; c) chickens; and d) distribution of ducks, excluding South America and Africa. Source: Robinson et al., 2014 (doi:10.1371/journal.pone.0096084.g002).

This last glimpse into the future of modelling livestock futures pertains to the vision of a spatially explicit global model of livestock production that could fill the vacant space in the landscape of existing models. A high-resolution spatial representation of livestock in MAgPIE has to be based on local processes of resource allocation and to account for relevant drivers of animal distributions. In analogy to the initial land mask prescribing land use patterns at the beginning of the simulation period in MAgPIE, the distribution of livestock species could be initialised by the improved version of the Gridded Livestock of the World (GLW2, see figure 2) database (Robinson et al., 2014).

Another important step of this endeavour consists in establishing feed balances on the level of spatial clusters instead of regions. While some feed groups like concentrates and feed industry byproducts (e.g. soymeal) are often transported over long distances and traded across regions, other feed sources have to be provided locally. Local feed balances ensure that low quality or perishable feed (e.g. crop residues, food waste, mowed or grazed biomass from pastures) is produced in the clusters where livestock is reared and the demand for feed occurs. Thus, local feed demand in combination with local nutrient supply from livestock manure, which can be used in the model to fulfil requirements for soil N_r inputs, would evolve as important drivers to determine the interplay between livestock, cropping and pasture patterns. The allocation of livestock to land can additionally be constrained by prescribing maximum stocking rates in accordance with different grazing management options and water availability for livestock drinking and servicing. Based on the existing implementation of intraregional transport costs, information about market access can guide the economic decision process where to allocate livestock and feed production.

Modelling the spatial distribution of livestock in MAgPIE can account for land allocation processes that are currently disregarded, thereby enhancing the overall quality of model projections. Moreover, such an extended model version allows for simulating environmental impacts of livestock production at a high spatial resolution and improves the assessment of local impacts of global environmental change on livestock. An important example of the latter is to more comprehensively model climate change impacts on the livestock sector. As pointed out by Herrero et al. (2015), the study presented in chapter II of this thesis represents an advancement in exploring impacts of climate change on livestock production. Nonetheless, we only focussed on impacts of climate change on the natural resource base of livestock production and investigated the indirect impacts on the livestock sector and the agricultural system arising from the changing availability and productivity of different feed types, thereby neglecting direct climate impacts on animals.

However, the thermal environment represents a key ecological factor that controls growth and productivity of different livestock species. Heat stress adversely affects production, reproductive performance and animal health (Gaughan, 2012; Nardone et al., 2010) and causes economic losses in the sector (St-Pierre et al., 2003). Even though climate change is likely to intensify heat stress, there is no global study available that addresses spatially explicit impacts of heat stress on livestock, neither for current nor for future conditions in a changing climate (Leclère and Havlík, 2016). Statistical models that establish a relationship between heat stress and livestock productivity could build an essential link connecting climate data and projections with a dynamic gridded representation of livestock in a global economic land-use model and pave the road towards a comprehensive and integrated assessment of both direct and indirect impacts of climate change on livestock.

Finally, the vision of "livestock on the land" in a global land use model could refine the assessment of environmental externalities of current and future livestock production as presented in the context of this thesis. The environmental significance of agricultural resource use and material flows often depends on the local context, as demonstrated e.g. in chapter IV with regard to agricultural fresh water use. N_r losses in the agricultural system also involve many detrimental impacts that operate on the local scale. Due to the importance of livestock production for the agricultural nitrogen cycle (chapter III), a dynamic gridded representation of livestock prepares the ground for a spatial modelling of air pollutants like NO_x and NH_3 as well as nitrate leaching, which is important to assess local pollution impacts like eutrophication and acidification of ecosystems, degradation of air quality and implications for human health.

Continuing the path that resulted in the development of the new model family of spatially explicit land use models, a new generation of these models could emerge that describe the livestock and the crop sector at the same level of detail regarding endogenous processes and spatial resolution. These models could further improve our understanding of agricultural activities in the Anthropocene and the connections between local impacts of global trends and global implications of local production realities. Between these poles of major broad-scale processes such as globalization, technological change, lifestyles, population growth and climate change on the one side and diverse site-specific circumstances of livestock rearing on the other side, the development of animal agriculture will significantly shape the future of agriculture and the sustainability of food production.

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Lists of tools, figures and tables

List of tools

The following tools were used for the modelling exercise and typesetting:

- GAMS (version 24.7.x; https://www.gams.com) with the CONOPT solver (https://www.gams.com/latest/docs/solvers/conopt/index.html)
- Inkscape (version 0.9x; https://inkscape.org/en/)
- Microsoft Office Word and Excel 2010 (version: 14.0.x (SP 2); https://www.microsoft.com/en-us/software-download/office).
- MiKTeX (version 2.9; https://miktex.org)
- R (version 3.x; https://www.r-project.org/), including the *Landuse library* developed at Potsdam Institute of Climate Impact Research
- TeXnicCenter (version 2.02; http://www.texniccenter.org)
- Zotero (Version 4.0.x; http://zotero.org)

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Declaration of independent work

"I declare that I have completed the thesis independently using only the aids and tools specified. I have not applied for a doctor's degree in the doctoral subject elsewhere and do not hold a corresponding doctor's degree. I have taken due note of the Faculty of Mathematics and Natural Sciences PhD Regulations, published in the Official Gazette of Humboldt-Universität zu Berlin no. 126/2014 on 18/11/2014."

Selbständigkeitserklärung

„Ich erkläre, dass ich die Dissertation selbständig und nur unter Verwendung der von mir gemäß § 7 Abs. 3 der Promotionsordnung der Mathematisch-Naturwissenschaftlichen Fakultät, veröffentlicht im Amtlichen Mitteilungsblatt der Humboldt-Universität zu Berlin Nr. 126/2014 am 18.11.2014 angegebenen Hilfsmittel angefertigt habe."

Potsdam, 2. Mai 2017

Isabelle Weindl